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ORIGINAL PAPER

Evaluation method of slope stability based on the Q_{slope} system and BQ method

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Abstract
At present, a variety of slope stability assessment methods based on rock mass quality classification have been proposed. However, the rather mature evaluation system for different types of rock slopes is still absent. In this paper, the existing classification methods for rock slope are first discussed, then by combining the Q_{slope} and BQ methods based on the relationship between different classification systems, a relatively simple and applicable evaluation system is proposed, which uses the BQ method to obtain the basic quality of the rock slope and then the Q_{slope} method to revise this rating according to the geological environment of the slope. The new system can reduce field survey and subjective factors. The case study shows that the evaluation results of the rock slope using the new method coincide with the actual stability status, showing that this method can be further tested in engineering practice.

Keywords Rock slope · Rock mass quality classification · Slope stability

Introduction

The stability evaluation methods of rock slope usually include the limit equilibrium method, numerical calculation method, physical simulation method, rock mass quality classification method, and so on. Among them, the first three methods, especially the limit equilibrium method, are mainly applicable to the slopes which have obvious or potential sliding surfaces. Otherwise, its use will be limited, such as in the case of natural slopes without obvious deformation or excavated slopes. The numerical models seldom coincide with the actual slope due to complex geological structure, and thus the reliability of the calculation results is questionable. Consequently, the stability of natural slopes or excavated rock slopes, which have no obvious signs of deformation, is often evaluated by the method of rock mass quality classification.

Based on the rock mass rating (RMR) method, Romana (1985) and Romana et al. (2003) first proposed the slope mass rating (SMR) system to evaluate rock slope stability. After that, many other methods evaluating rock slope quality have been put forward one after another, which include rock mass strength (RMS, Selby 1980), slope rock mass rating (SRMR, Robertson 1988), Chinese slope mass rating (CSMR, Chen 1995; Sun et al. 1997), rock slope deterioration assessment (RDA, Nicholson and Hencher 1997), slope stability probability classification (SSPC, Hack et al. 2003), volcanic rock face safety rating (VRFSR, Singh and Connolly 2003), falling rock hazard index (FRHI, Singh 2004), and the method used for assessing nature slope stability by Mazzocola and Hudson (1996). In China, Shi et al. (2005) put forward the highway slope mass rating (HSMR) fast evaluation system for the stability of layered rock slopes along mountain highways. Zhang et al. (2010), taking rock slopes along the Tianshan mountain highway as an example, proposed the Tianshan highway slope mass rating (TSMR) for slope stability evaluation in high altitudes and cold regions, which is based on the RMR, SMR, and CSMR rock mass rating systems, where the correction coefficient ξ of slope height and condition coefficient λ of structural plane are adjusted by using mathematical statistics tools, and freeze-thaw coefficient δ is also introduced.

Among the above methods, SMR is the most widely used and is the base of most of the other methods.

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The basic quality (BQ) system is regarded as the Chinese national rock mass classification system (GB/T 50218-2014 2014) that can be appropriate for use in most types of rock engineering. Two underlying parameters, the uniaxial compressive strength (UCS) and the rock intactness index (K_v), are considered to assess the basic BQ value. For rock slope engineering, considering the adverse impact of the existing geological conditions, the BQ value is adjusted to corrected [BQ] by introducing five coefficients of correction to determine the rock slope rating. The BQ system is only applied to rock slopes less than 60 m in height with sliding failure mode.

Barton and Bar (2015) and Bar and Barton (2017) developed a Q_{slope} method to evaluate the stability of rock slopes, which is based on the Q system rock mass quality classification (Barton et al. 1974; Barton 2002), by adjusting the index meaning and parameter values in the original system to make it qualified for the work. In addition, based on many engineering examples in Asia, Australia, Central America, and European countries, the relationship between the Q_{slope} value and slope angle that can maintain long-term slope stability under the condition of unsupported is established. However, this system cannot be applied to slopes with interbedding of soft and hard rocks or with weak rock layers, as well as in soil slopes or talus and debris.

Compared to the BQ method, the Q_{slope} system is more widely applicable. However, it utilizes six parameters RQD, J_n, J_r, J_a, J_{wice}, and SRF_{slope}, and the first four parameters which determine the basic quality of rock mass Q' need to be observed carefully in the field. Different geologists may vary the value of each parameter, thereby getting different results. The BQ method only uses UCS and K_v, both of which are quantitative indexes, thus reducing the subjective factors of the geological engineer to judge rock mass basic quality. Based on the above, a relatively simple and applicable evaluation system is proposed by combining the Q_{slope} and BQ method, which not only reduces field survey but also subjective factors to a certain extent.

Q_{slope} and BQ system

Q_{slope} system

For Q-system users, the formula for estimating Q_{slope} is mostly familiar (Barton and Bar 2015; Bar and Barton 2017):

$$Q_{slope} = \frac{RQD}{J_n} \times \left(\frac{J_r}{J_a}\right)_o \times \frac{J_{wice}}{SRF_{slope}} \quad (1)$$

Here:

RQD is the rock quality designation, which varies between 0 and 100; if its value is ≤10 (including zero), then a nominal value of 10 is used to evaluate the Q_{slope}.

J_n is the joint set number that maintains the values established in the Q system.

J_r and J_a are the joint roughness number and the joint alteration number, respectively, and maintain the values of the Q system. The factor $(J_r/J_a)_o$ considers the favorable or unfavorable orientation of the major discontinuity or of those forming a wedge by an adjustment factor referred to as the "O-factor".

J_{wice} is the environmental and geological condition number that substitutes the joint water reduction factor (J_w) of the Q system.

SRF_{slope} is the stress reduction factor for the slope, the maximum value among SRF_a (which deals with physical condition), SRF_b (which addresses both in situ stress and UCS of the rock, similarly to the one used in the Q system), and SRF_c (which considers major discontinuity).

The reader is referred to the work of Barton and Bar (2015) and Bar and Barton (2017) for a detailed description and weighting of each of the aforementioned factors. A simple equation for the steepest angle (β), which does not require reinforcements for slope, is established by Barton and Bar (2015) and Bar and Barton (2017):

$$\beta = 20\log_{10}Q_{slope} + \alpha \quad (2)$$

Table 1 The correction factor K_4 in the [BQ]

Ground water conditions	Correction factor K_4				
	BQ>550	550 ≥ BQ ≥ 451	450 ≥ BQ ≥ 351	350 ≥ BQ ≥ 251	BQ ≤ 250
Wet or dripping, p_w<0.2H	0.0	0.0	0.0–0.1	0.2–0.3	0.4–0.6
Threadlet-like flowing, 0.2H<p_w ≤ 0.5H	0.0–0.1	0.1–0.2	0.2–0.3	0.4–0.6	0.7–0.9
Gushing, p_w>0.5H	0.1–0.2	0.2–0.3	0.4–0.6	0.7–0.9	1.0

Here: p_w is the phreatic water or artesian head (m) in the slope, H is the slope height (m)

Table 2 The correction factor λ in the [BQ]

Discontinuities types and extensibility	Correction factor λ
Fault, weak intercalation	1.0
Bedding plane, joint or fracture with good connectivity	0.9–0.8
Interrupted joint or fracture	0.7–0.6

Here:

- β is the steepest angle to maintain slope stability not requiring reinforcements.
- Q_{slope} is the value obtained from formula 1.
- α is the angle corresponding to the different failure probability, i.e., when the failure probability is 1%, 15%, 30%, 50%, the α value is 65°, 67.5°, 70.5°, and 73.5°, respectively.

BQ method

The BQ method was first proposed to evaluate the stability of engineering rock mass and assist the support selection, and it is recommended as the only national guideline that satisfied most various rock engineering fields, such as hydropower underground caverns, railway or highway tunnels, building foundations, coal mines, and so on. A linear regression equation determining the BQ value was expressed as follows in the national standard called *Standard for Engineering Classification of Rock Mass* (GB/T 50218-2014 2014):

$$BQ = 100 + 3R_C + 250K_V \tag{3}$$

Here:

- BQ is the rock mass basic quality.
- R_c is the uniaxial compressive strength (UCS), in MPa.
- K_v is the rock intactness index, which can be calculated from the acoustic velocity of rock mass, V_{pm}, and the intact rock velocity, V_{pr}, using the following formula:

$$K_V = \frac{V_{pm}^2}{V_{pr}^2} \quad 0 \le K_V \le 1 \tag{4}$$

During the application of Eq. 3, two important constraint criteria should be noticed: (1) when $R_c > 90\,K_v + 30$, then the value of $90\,K_v + 30$ should be used for R_c to determine the BQ value; (2) when $K_v > 0.04\,R_c + 0.4$, then K_v should be calculated from the equation $K_v = 0.04\,R_c + 0.4$ to obtain the BQ value.

For rock slope engineering, the BQ value derived from Eq. 3 should be revised considering the adverse impact of the existing geological and environment conditions, the revised formula being:

$$[BQ] = BQ - 100(K_4 + \lambda K_5) \tag{5}$$

Here:

- [BQ] is the revised value of BQ.
- BQ is the rating for rock mass basic quality, which can be calculated from Eq. 3.
- K_4 is the correction factor of groundwater conditions (see Table 1).
- λ is the correction factor for key discontinuities types and extensibility, which is the same as the CSMR method (Chen 1995; Sun et al. 1997), see Table 2.
- K_5 is the correction factor for key discontinuities attitude, which can be expressed as follows:

$$K_5 = F_1 \times F_2 \times F_3 \tag{6}$$

Here:

- F_1 is related to the relationship between dip direction of key discontinuity and slope
- F_2 is the correction factor of dip angle for key discontinuity
- F_3 concerning the relationship between dip angle of key discontinuity and slope (see Table 3).

Table 3 The correction factors F_1, F_2, and F_3 in the [BQ]

Conditions and correction factor	Influence degree				
	Slight	Less	Moderate	Remarkable	Significant
The angle between dip direction of key discontinuity and slope surface (°)	>30	30~20	20~10	10~5	≤5
F_1	0.15	0.40	0.70	0.85	1.0
Dip angle of discontinuity (°)	<20	20~30	30~35	35~45	≥45
F_2	0.15	0.40	0.70	0.85	1.0
The difference between dip angle of discontinuity and slope angle	>10	10~0	0	0~− 10	≤− 10
F_3	0	0.2	0.8	2.0	2.5

Table 4 Rock slope classification and stability based on [BQ]

Class	[BQ]	Description
I	>550	The slope can retain long-term stability
II	451–550	The slope can retain long-term stability when its height is less than 30 m, for the slope range of 30–60 m in height, the slope will be basically stable, wedge failure may occur locally
III	351–450	The slope will be basically stable if the slope height is less than 15 m, wedge failure may also occur locally, for slope height of 10–15 m, which can remain stable for a few months
IV	251–350	The slope can remain stable for a few months or no more than 1 month for slope height less than 8 m or 8–15 m, respectively
V	≤250	Unstable

The [BQ] method classifies all slope rock masses into five classes (same as BQ). The boundary values of each class and slope stability status are listed as Table 4.

The [BQ] rock mass quality classification for slopes is only applicable to slopes with height less than 60 m, and only sliding failure is considered. Therefore, it has certain limitations in engineering application.

BQ-Q_{slope} system

Bar and Barton (2017) suggest that Q_{slope} applies to all slope heights and slope angles that range between 30°and 90°, which covers most of the rock slopes, thus having a broad application prospect. However, the first four parameters in this system, RQD, J_n, J_r, and J_a, need to be observed carefully in the field and maybe different geologists have different results. To overcome this shortcoming, the BQ method is introduced to reduce the number of parameters in the Q_{slope} system and improve the objectivity of the method.

According to the regression analysis of more than 200 sets of measured BQ values and RMR based on more than ten projects involving hydropower plants and highways, the Chinese national standard called the *Standard for Engineering Classification of Rock Mass* (The National Standards Compilation Group of People's Republic of China 2014) reveals a good linear relationship between the BQ value and the RMR as follows:

$$\mathrm{BQ} = 80.786 + 6.0943\mathrm{RMR} \quad (r = 0.81) \tag{7}$$

Here:

RMR is the revised rating value of the Bieniawski rock mass classification from 1989.

In addition, according to Hoek et al. (1995), the relationship between RMR and GSI, GSI and Q′ can be expressed as follows:

$$GSI = RMR'_{89} - 5 \tag{8}$$

$$\mathrm{GSI} = 9\ln Q' + 44 \tag{9}$$

Here:

GSI is the geological strength index.

RMR'_{89} is the revised rating value of the Bieniawski rock mass classification from 1989, which is for dry condition. The corresponding groundwater parameter is 15. Formula 7 becomes the following when taking groundwater into account:

$$\mathrm{BQ} = 80.786 + 6.0943\left(\mathrm{RMR}'_{89} - 15\mathrm{G_C}\right) \tag{10}$$

Here:

G_c is the correction coefficient of groundwater, and its value is between 0 and 1. The Bieniawski rock mass classification and the G_c scoring criteria are shown in Table 5.

Q′ representing the basic quality of rock slope in the Q_{slope} system, which is:

$$Q' = \frac{\mathrm{RQD}}{J_n} \times \frac{J_r}{J_a} \tag{11}$$

After formulas 8 and 10, the relationship between BQ and GSI is as follows:

$$\mathrm{GSI} = 0.164\mathrm{BQ} - 18.256 + 15\mathrm{G_C} \tag{12}$$

Table 5 The correction factor Gc of BQ-Q_{slope} system

Groundwater conditions	Completely dry	Damp	Wet	Dripping	Flowing
Correction factor Gc	0	0.33	0.53	0.73	1

Fig. 1 The Moon River valley slope

Similarly, from formulas 9 and 12, the expression of Q′ using BQ is:

$$Q' = EXP(0.0182BQ-6.9173 + 1.667G_C) \quad (13)$$

To be more simplified, formula 13 can also be written by:

$$Q' = 0.001 \times 5.945^{G_C} \times EXP(0.018BQ) \quad (14)$$

Combining formulas 1 and 14, Q_{slope} can be simplified by:

$$BQ-Q_{slope} = \lambda \times EXP(0.018BQ) \quad (15)$$

Here:

λ is the correction factor, $\lambda = 0.001 \times 5.294^{G_C} \times F_1 \times F_2 / \times F_3$, F_1, F_2, and F_3 are the O-factor, J_{wice}, and SRF_{slope}, respectively, in the Q_{slope} system.

Using BQ-Q_{slope} (formula 15) to replace the Q_{slope} in formula 2, we can get the steepest slope angle maintaining slope stability as formula 16 (the failure probability is 1%):

$$\beta = 0.156BQ + 20\log_{10}\lambda + 65 \quad (16)$$

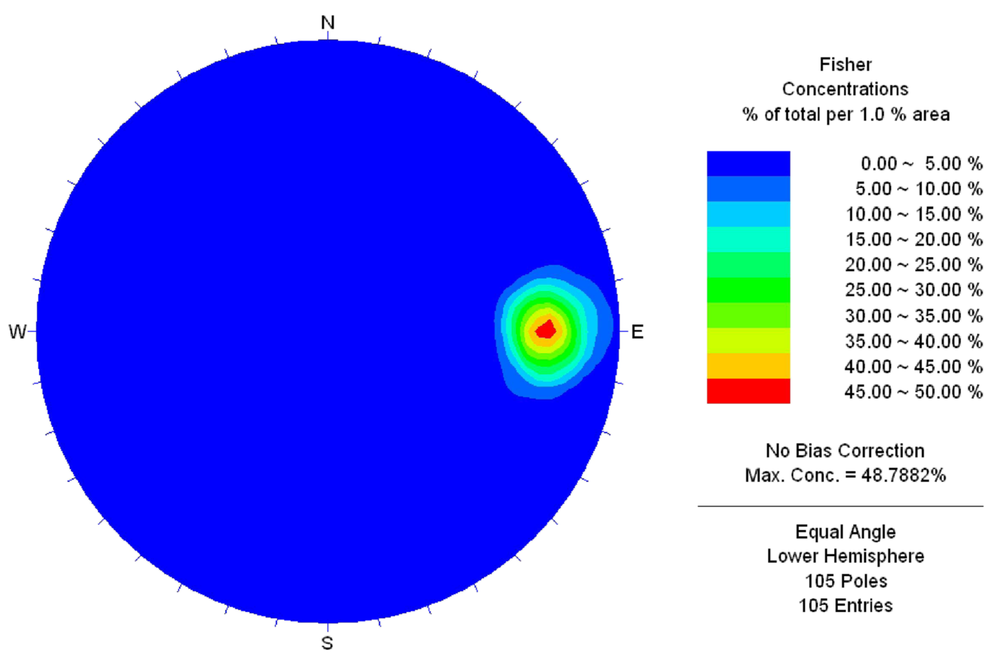
From formulas 3 and 16, it can be seen that the first four parameters (RQD, J_n, J_r, and J_a) in the Q_{slope} system are replaced by two parameters (UCS and Kv) in the BQ method, which need to be measured accurately in the field work. The former can be measured using a portable point loader and the latter using a sonic instrument or through measuring J_v. Based on the above and taking into account the existing geological and environment conditions of the slope, the stability status of the slope can be instantly estimated.

Limits of applicability of the BQ-Q_{slope} system

For rock mass with poor quality, the GSI value cannot be estimated by the RMR'_{89} value. Referring to related literature, the GSI = RMR'_{89}-5 formula is established on the condition that $RMR'_{89} > 23$. According to formula 10, BQ > 220.59-91.41G_c, where G_c is between 0 and 1. The G_c values under different conditions can be looked up in Table 5.

In addition, it can be seen from the above that the BQ-Q_{slope} system only replaces Q′ in the Q_{slope} method with BQ by means of the relationship among BQ, RMR, GSI, and Q′ and without any changes to other parts. Therefore, the application conditions of the BQ-Q_{slope} system are consistent with that of Q_{slope}, and there is no restriction on slope height.

Fig. 2 The contours of joints in the left slope rock mass



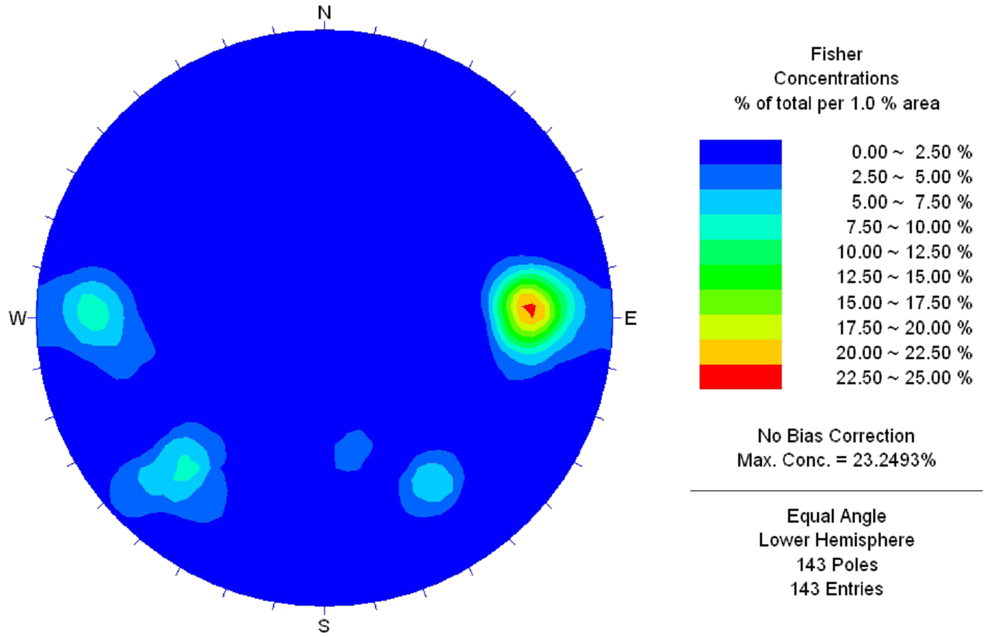


Fig. 3 The contours of joints in the right slope rock mass

Case study

The Zhen'an Pumped Storage Power Station is located in the Territory of Yuehe Township, Shangluo City, Shaanxi Province, 128 km from Xi'an. The power station hub consists of the upper reservoir, the lower reservoir, water conveyance system, underground powerhouse, switch station, and other components. Among them, the lower reservoir is located in the main stream of the Moon River, which trends approximately SE120~150° and the river elevation is between

Table 6 The left bank slope rock mass quality by BQ-Q_{slope} and Q_{slope} methods

Adit section (m-m)	Weathering degree	Major joints attitude	Effect of major joints on slope stability	Lithology	UCS (MPa)	Rock intactness index K_v	RQD(%)	J_n	J_r	J_a	G_c
0–5	Intensely	270°∠74°	Favorable	Granodi-orite	55	0.04	6	18	1	3	0
5–10						0.19	56	20	1	3	0
10–15	Moderately				72	0.06	71	18	1	5	0
15–20						0.52	86	9	1	3	0
20–25						0.47	88	9	1	3	0
25–30						0.55	81	4	1	3	0
30–35						0.52	73	4	1	3	0
35–40						0.47	86	9	1	3	0
40–45						0.45	74	9	1	3	0
45–50						0.62	85	4	1	3	0
50–55						0.57	81	12	1	3	0
55–60						0.62	88	2	1	3	0
60–65	Slightly				96	0.33	82	2	1	3	0
65–70						0.36	89	2	1	3	0
70–75						0.36	84	4	1	3	0
75–80						0.36	89	4	1	3	0
80–85						0.43	90	2	1	3	0
85–90						0.38	92	2	1	3	0
90–95						0.28	70	9	1	3	0
95–100						0.23	80	4	1	3	0

Rock intactness index K_v is estimated from volumetric joint count J_v, which is obtained by measuring the joints along the adit wall

Table 7 The right bank slope rock mass quality by BQ-Q_{slope} and Q_{slope} methods

Adit section (m-m)	Weathering degree	Major joints attitude	Effect of major joints on slope stability	Lithology	UCS (MPa)	Rock intactness index K_v	RQD(%)	J_n	J_r	J_a	G_c
0–5	Intensely	267°∠70°	Favorable	Granodi-orite	55	0.31	42	20	1	3	0
5–10						0.26	66	9	1	3	0
10–15	Moderately				72	0.59	71	15	1	4	0
15–20						0.62	82	4	1	3	0
20–25						0.62	81	9	1	3	0
25–30						0.64	86	4	1	3	0
30–35						0.57	68	12	1	3	0
35–40						0.47	52	9	1	4	0
40–45						0.28	51	4	1	3	0
45–50		42°∠70°				0.30	51	12	1	3	0
50–55						0.69	86	4	1	3	0
55–60						0.67	81	4	1	3	0
60–65		267°∠70°				0.94	92	2	1	3	0
65–70		327°∠68°	Very favorable			0.59	66	12	1	3	0
70–75						0.38	44	4	1	3	0
75–80		42°∠70°	Favorable			0.35	50	9	1	3	0
80–85		267°∠70°				0.38	46	15	1	3	0
85–90						0.55	60	12	1.5	3	0

Rock intactness index K_v is estimated from volumetric joint count J_v, which is obtained by measuring the joints along the adit wall

960~822 m. The Moon River valley shows a V-shaped profile with bottom width of 40–60 m. The bank slope is steep from the bottom of the valley to above 50 m, usually at 50~70° with local steep cliffs, and the upper part of the slope is usually at 40~45°. The total height of the bank slope is about 130~150 m. Typical valley shape is shown in Fig. 1.

The lower reservoir bank slope at the dam site trends about SE170°, formed by Mesozoic grayish-white granodiorite with hypautomorphic granular texture. The slope structure is characterized as blocky.

There are no regional large faults passing through the dam site except for some minor faults. The rock joints developed in the slope show mostly steep angles. For the left bank slope, there is only one joint set striking nearly S-N with E or W dip direction, dip angle about 74° (Fig. 2). In the right bank slope, four joints sets are found in the rock mass, the detailed information is depicted in Fig. 3.

For the sake of stability evaluation of the bank slope at the dam site and thus supporting the design of excavation, two exploratory adits have been excavated, one in the middle part of the left slope and the other in the right one. The slope angles in different adit segments are estimated by using Q_{slope} and Q_{slope}-BQ systems for comparison, so as to verify the correctness of the Q_{slope}-BQ system.

Through the measurement and test work along the adit wall, the rock's degree of weathering, UCS, and the rock

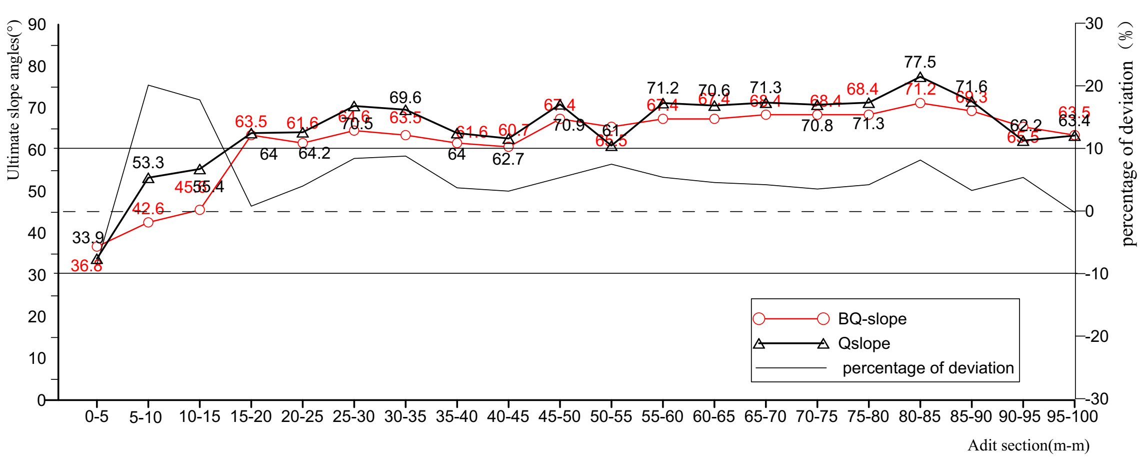


Fig. 4 The left bank slope ultimate slope angles

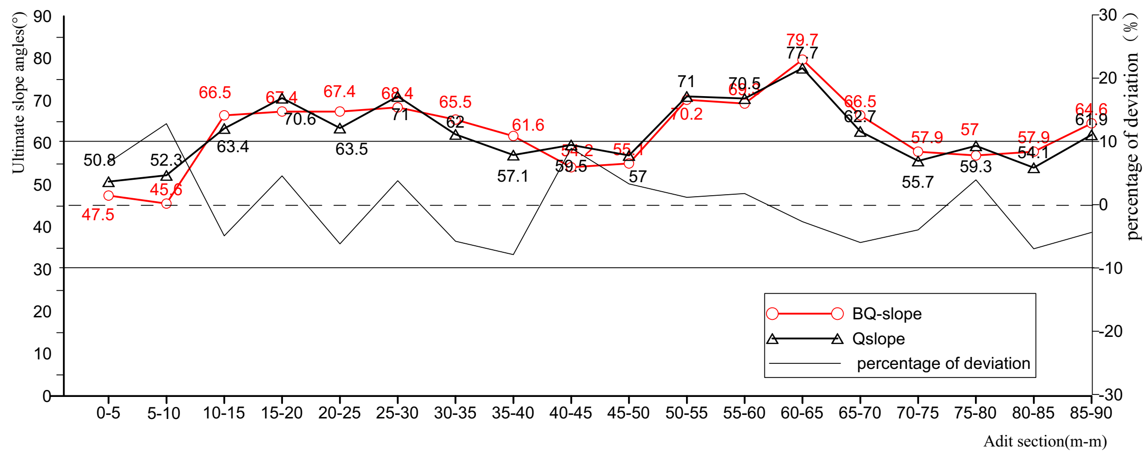


Fig. 5 The right bank slope ultimate slope angles

intactness index in different adit segments have been obtained, which would been used in the BQ-Q_{slope} system. RQD, J_n, J_r, and J_a are used in the Q_{slope} system. The results are shown in Tables 6 and 7.

In addition, the joints both in the left and right bank slope are all favorable to the stability of the slope. Therefore, the O-factor should be 1.0; the J_{wice} factor should be 0.7 because the study site is located in the transition section of the north subtropical zone to the warm temperate zone with annual rainfall of about 800 mm, which belongs to the semi humid climate and wet environment. The slope structure is favorable to the stability, and the rock (granodiorite) that constitutes the slope is a competent rock; so the factors SRF_a, SRF_b, and SRF_c should be 2.5, 2.5, and 1.0, respectively, according to the geological conditions of the slope, and thus the maximum value 2.5 should be chosen as the factor SRF_{slope}. In addition, the slope is in a dry state as a whole, and the value of G_c is 0.

Based on the above, the ultimate slope angles corresponding to the different excavation depths in the horizontal direction are calculated from Q_{slope} and Q_{slope}-BQ systems, respectively, and the results are shown in Figs. 4 and 5 (failure probability is 1%).

The above results show that the lower reservoir bank slope at the dam site can usually remain stable in a steep slope angle apart from the highly weathered rock mass in the slope shallow surface. This is in accordance with the actual situation of the river valley slope; for example, the lower part of the slope is often steep due to slightly weathered rock, but in the upper part, the slope angle is relatively small to maintain the stability of the slope due to highly weathered rock and poor intactness. The field investigation shows that the slope angle of the upper part is generally 40~45°, which is in agreement with the calculation results (the left bank slope is 37~46° and the right is about 46~48°). This fact shows that the evaluation method of slope stability presented in this paper is applicable.

In addition, it can be seen that the slope angle estimated by Q_{slope} and Q_{slope}-BQ methods is basically the same except at the entrance of the adits, and the percentage of deviation basically within 10%. Therefore, it is feasible to replace four parameters of Q_{slope} with two parameters of the BQ system to estimate slope angle.

At the entrance of the adits, with developed fractures and fractured rock mass, the integrity index K_v obtained from volumetric joint count J_v is low, resulting in a relatively low BQ value in the BQ-Q_{slope} method. However, the fitting degree of the two results is higher for the intact rock mass in the adits.

Conclusions

The Q_{slope} method used for slope stability evaluation is based on the rock mass classification method Q system, which needs to take into account the rock quality index RQD, the number of rock joint sets, the joint roughness, and alteration through detailed investigation in the field. The BQ method only employs two parameters, UCS and rock intactness index K_v, both of which are quantitative indexes and easy to obtain through laboratory or field tests and measuring. In this paper, the BQ-Q_{slope} method is put forward through combining the BQ method and Q_{slope} system based on the relationships between different rock mass classification methods, which not only simplifies the field survey but also makes the results more objective. The case study shows that evaluation results using the method presented in this paper are coherent with what is observed; however, due to the lack of application, further studies are required in more engineering projects to improve and expand the application of the method.

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