

Rock bolt supporting factor: rock bolting capability of rock mass

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Abstract Rock mass classification has played a crucial role in underground construction and mining projects in the past fifty years, especially the Rock Mass Rating (RMR) and Rock Tunneling Quality Index (Q) systems, which have been applied in many cases. The parameters of discontinuity conditions in the RMR system, along with the related ratings, were used to develop a new equation in order to introduce an intrinsic quality of a given rock mass, namely, rock bolt supporting factor (RSF). The RSF was used to develop a mathematical theory of the rock bolt supporting mechanism as a new principle in explaining rock bolting effects. Finally, using the parameters of the discontinuities in the Q-system, the QRSF is defined to present the capability of a given rock mass to be reinforced by rock bolting. The RSF leads to more reliable judgment of rock bolting capability of a given rock mass than the QRSF since it uses five parameters of discontinuity conditions while the QRSF uses only two parameters.

Keywords Rock bolt · Reinforcement capability · Rock mass classification · RMR · Q system

Introduction

Rock mass classifications form an integral part of the empirical design methods in mining and civil works which have provided the only systematic design aid in many cases of underground construction and mining projects (Bieniawski 1989). The first rock engineering classification system was proposed for tunneling with steel ribs by Terzaghi (1946). In this method, rock loads on the steel sets can be estimated through a descriptive classification which categorizes rock masses into intact, stratified, moderately jointed, blocky and seamy, crushed, squeezing and, finally, swelling rock. Classification involving stand-up time was introduced by Lauffer (1958). He proposed that the quality of surrounding rock mass determines the stand-up time of unsupported spans of an excavation. An unsupported span is defined as the span of the tunnel or the distance between the face and nearest support, if this is greater than the tunnel span. Lauffer's original classification was modified by Pacher et al. (1974), leading to introduction of a general tunneling approach known as the New Austrian Tunneling Method (NATM).

Deere et al. (1967) developed a rock quality designation (RQD) index to provide a quantitative description of rock mass quality from drill core logs. The RQD is defined as the percentage of core pieces longer than 10 cm in the overall length of a core. In case where no cores are available but discontinuity traces can be seen, Palmstrom's (1982) equation (Eq. 1) for clay-free rock masses can be used to obtain RQD values where J_v is the sum of the number of joints per unit length for all discontinuity sets, known as volumetric joint count.

$$RQD = 115 - 3.3J_v \quad (1)$$

A quantitative method known as rock structure rating (RSR) was introduced by Wickham et al. (1972) in order

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to describe rock mass quality and select appropriate supporting systems based on this method. The RSR system was the first to feature classification ratings for weighting the relative importance of classification parameters. Numerical RSR values with a maximum of 100 can be obtained as a result of summing the ratings attributed to each component of the system, namely: A, B and C where A is related to geological rock mass features, B is related to geometry (effect of discontinuity pattern with regard to tunnel drive) and C represents the effect of groundwater with regard to joint conditions. After calculation of the RSR value, the supporting system for the tunnel can be estimated from curves proposed for this purpose.

Geomechanics classification, also known as the Rock Mass Rating (RMR) system, was developed by Bieniawsky (1973). As more case histories became available and to conform with international standards and procedures, the original RMR system was modified several times over the years. To classify a rock mass using the RMR system, six parameters, namely uniaxial compressive strength (UCS), rock quality designation (RQD), spacing of discontinuities, condition of discontinuities, groundwater conditions and orientation of discontinuities, are used (Bieniawsky 1989). This classification system will be thoroughly discussed since discontinuity conditions, as one of the input parameters in this classification system, are one of the main concerns in determining the rock bolt supporting factor (RSF) of a rock mass.

Using six parameters, namely RQD, number of joint sets, roughness of the most unfavorable joint or discontinuity, degree of alteration or filling along the weakest joint, water inflow and stress condition, Barton et al. (1974) defined the Rock Tunneling Quality Index (Q) as an equation two where the first quotient (RQD/J_n) represents the block size in the rock mass, the second quotient (J_r/J_a) represents the roughness and frictional characteristics of the joint walls or filling materials, and the third quotient (SRF/J_w) consists of two stress parameters.

$$Q = \frac{RQD J_r J_w}{J_n J_a SRF} \quad (2)$$

In this paper, RSF is introduced as an intrinsic quality of a rock mass based on the condition of discontinuities in the RMR system. The RSF is also used to develop a mathematical theory on the rock bolting mechanism as well as some other applications which specify the capability of a given rock mass to be reinforced by rock bolting. Afterwards, a similar factor was developed based on the Q-system of rock mass classification, and the applicability of this factor is discussed.

RMR: a theoretical excursion

Geomechanics classification, also known as the RMR system, was developed by Bieniawsky (1973). However it has been subsequently modified several times and is mainly used as a design guideline in tunneling practices. Also, some valuable applications of the RMR system, as mentioned by Bieniawsky (1989), include: mining applications (Laubscher 1977, 1984); rippability (Weaver 1975); hard rock mining (Kendorski et al. 1983); coal mining (Unal 1983; Newman and Bieniawski 1986); dam foundations (Serafim and Pereira 1983); tunneling (Gonzalez de Vallejo 1983); slope stability (Romana 1985); and Indian coal mines (Venkateswarlu 1986).

The RMR system uses six parameters, namely: UCS, RQD, spacing of discontinuities, condition of discontinuities, groundwater conditions and orientation of discontinuities, to classify a rock mass. After establishing the importance ratings for these classification parameters, the ratings for the first five parameters are summed to yield the basic (unadjusted for discontinuity orientations) RMR value which varies from 0 to 100. The sixth parameter (strike and dip orientation of discontinuities) is treated separately due to its dependency on engineering application of underground excavations such as mines, tunnels, slopes or foundations (Bieniawsky 1989).

The parameter 'condition of discontinuities' consists of five characteristics, each with a maximum rating of 6. The maximum aggregate value of these 5 parameters is 30, which is the maximum rating of discontinuity conditions. The aforementioned five parameters include discontinuity length (persistence/continuity), separation (aperture), roughness, infilling (gouge) and weathering. Guidelines for classification of discontinuity conditions is presented in Tables 1 and 2. The maximum allocated ratings for UCS (rating: 15), RQD (20), spacing of discontinuities (20), condition of discontinuities (30) and groundwater conditions (15) are summed to yield the maximum theoretical value of basic RMR as 100. In determining the RSF, the sixth parameter of the RMR system, orientation of discontinuities, is not used because it's not an intrinsic property of a rock mass as defined with regard to the tunnel axis.

Different combinations of the parameters comprising the basic RMR to yield the values of 85, 74, 45 and 25 are shown in Tables 3, 4, 5 and 6, respectively. The main question here is whether there is any difference among the rock types described in states A to D of Table 3 while the RMR values are the same and, if so, what is the difference. These questions are also considerable for Tables 4, 5 and 6 which demonstrate the different combinations of input parameters to yield other basic RMR values in each case.

Table 1 Guidelines for classification of discontinuity conditions (after Bieniawski 1989)

Parameter	Ratings				
	<1 m	1–3 m	3–10 m	10–20 m	>20 m
Discontinuity length (persistence/continuity)	6	4	2	1	0
	None	<0.1 mm	0.1–1 mm	1–5 mm	>5 mm
Separation (aperture)	6	5	4	1	0
	Very rough	Rough	Slightly rough	Smooth	Slickensided
Roughness	6	5	3	1	0
	Hard filling			Soft filling	
Infilling (gouge)	None	<5 mm	>5 mm	<5 mm	>5 mm
	6	4	2	2	0
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
	6	5	3	1	0

Some conditions are mutually exclusive. For example, if infilling is present, it is irrelevant what the roughness may be, since its effect will be overshadowed by the influence of the gouge. In such cases, Table 2 should be used directly.

Table 2 Guidelines for classification of discontinuity conditions (after Bieniawski 1989)

Condition of discontinuities	Very rough surfaces, not continuous, no separation, unweathered wall rock	Slightly rough surfaces, separation <1 mm, slightly weathered walls	Slightly rough surfaces, separation <1 mm, highly weathered wall	Slickensided surfaces or gouge, <5 mm thick or separation 1–5 mm continuous	Soft gouge >5 mm thick or separation >5 mm continuous
Rating	30	25	20	10	0

The key issue to consider is the point of view from which these rock types are being viewed. For example, to assess the rock mass quality for tunneling and stability purposes, there may be no difference between the rock masses with the same RMR values with different combinations of parameters. However, considering the reinforcement capability of rock mass by rock bolting or grout injection practices, there is a considerable difference between these rock masses as the discontinuity conditions differ in each case. These differences will be explained and formulated as the RSF, which indicates the intrinsic capability of a given rock mass to be reinforced by rock bolting.

RSF

The RMR value for a type of rock mass which has no discontinuity sets will be dependent on the UCS, ranging from 85 to 100 and fitting into class I of the RMR classification. So is the RMR value of completely dry rock masses with an RQD value of 100 %, spacing of discontinuities more than 2000 mm and condition of discontinuities being as column 2 of Table 1 (overall rating of 30). Therefore, the existence of discontinuities in case 2 has no effect on the reduction of the RMR value for the supposed

rock mass. This is due to the RMR system focusing on the behavior of discontinuities and their contribution to the rock mass behavior.

Paying close attention to the details of discontinuity conditions, as presented in Table 1, reveals the fact that the ratings for each parameter are allocated according to the degree of its participation in the increase of shear resistance of the discontinuity surface. For instance, very rough surfaces will cause more resistance than smooth surfaces due to which the rating for very rough surfaces is more than that of smooth surfaces. Also, tight discontinuities have more impact than open ones, the existence of infilling material will cause decrease of shear resistance, and unweathered surfaces have more ratings than decomposed ones. A lower persistence of discontinuities means a lower decrease of shear resistance. Regarding this point, increasing the friction of discontinuity surfaces can cause a noticeable impact on the reinforcement of rock masses.

A properly designed rock bolting system, precluding rock blocks from sliding due to increased shear resistance of the discontinuity surfaces, can cause an increase in the rating of discontinuity condition parameters, namely persistence, aperture, roughness, infilling and weathering, from their initial values to maximum values of 6, the sum of which produces the maximum aggregate rating of 30 for

Table 3 Different combinations of parameters to yield the basic RMR value of 85

State Parameter	A RMR = 85	B RMR = 85	C RMR = 85	D RMR = 85
UCS (Mpa)				
Value	260	260	110	260
Rating	15	15	10	15
RQD (%)				
Value	85	90	100	100
Rating	17	18	20	20
Spacing				
Value	200 mm	650 mm	2200 mm	2200 mm
Rating	8	12	20	20
Condition of discontinuities				
Persistence				
Value	<1 m	1–3 m	Slightly rough surfaces	10–20 m
Rating	6	4	Separation <1 mm	1
Aperture				
Value	None	<0.1 m	Highly weathered wall	0.1–1 mm
Rating	6	5		4
Roughness				
State	Very rough	Rough		Smooth
Rating	6	5		3
Infilling				
Value	None	None		None
Rating	6	6		6
Weathering				
State	Unweathered	Slightly weathered		Highly weathered
Rating	6	5	20	1
Groundwater [inflow per 10 meter tunnel length (L/min)]				
State	Completely dry	Completely dry	Completely dry	Completely dry
Rating	15	15	15	15

condition of discontinuities. In fact, a properly designed rock bolting system does not eliminate the aperture, persistence or other characteristics of discontinuities. However, it increases the shear resistance of discontinuities to their maximum and since the RMR ratings are interested in the shear behavior of discontinuities, it is reasonable to consider the complex of rock mass and rock bolts as an equivalent rock mass with the overall discontinuity rating of 30. For example, the overall rating of discontinuity conditions in state C of Table 3 (which is 20) can be increased 10 points to reach the maximum of 30. Therefore, the increase of 10 points is the capability of the rock mass to be reinforced by rock bolting. These values for states A, B and D of Table 3 are 0, 5 and 15, respectively. Therefore, the capability of a rock mass to be reinforced can be defined as a percent of the overall discontinuity condition rating. This definition is presented as Eq. 3 where r_{co} is the overall rating for the condition of

discontinuities. The results are multiplied by 100 to be in accordance with the RMR values and the mathematical [] sign was used to omit the decimal part of the obtained values, which can range from 0 (for $r_{co} = 30$) to 100 (for $r_{co} = 0$) where $RSF = 100$ shows the greatest capability of a given rock mass to be reinforced by rock bolting.

$$RSF = \left[100 \times \frac{30 - r_{co}}{30} \right] \quad (3)$$

Equation 3 can be rewritten as Eq. 4.

$$RSF = \left[100 - \frac{10 \times r_{co}}{3} \right] \quad (4)$$

RSF is an intrinsic property of a given rock mass which can be used to explain the difference of rock types with the same RMR values presented in Tables 3–6. Table 7 shows the RSF values for the aforementioned rock types. A higher RSF value for a given rock mass indicates a greater ability

Table 4 Different combinations of parameters to yield the basic RMR value of 74

State Parameter	A RMR = 74	B RMR = 74	C RMR = 74	D RMR = 74	E RMR = 74
UCS (Mpa)					
Value	68	125	80	200	165
Rating	7	11	8	14	13
RQD (%)					
Value	95	80	100	100	100
Rating	19	16	20	20	20
Spacing					
Value	500 mm	300 mm	2200 mm	1100 mm	2200 mm
Rating	11	9	20	15	20
Condition of discontinuities					
Persistence					
Value	<1 m	1–3 m	3–10 m	Slickensided surfaces or gouge <5 mm thick or separation 1–5 mm continuous	>20 m
Rating	6	4	2		0
Aperture					
Value	None	<0.1 mm	0.1–1 mm		>5 mm
Rating	6	5	4		0
Roughness					
State	Very rough	Slightly rough	Smooth		Slickensided
Rating	6	3	1		0
Infilling					
Value	None	None	None		None
Rating	6	6	6		6
Weathering					
State	Unweathered	Slightly weathered	Moderately weathered		Decomposed
Rating	6	5	3	10	0
Groundwater [inflow per 10 meter tunnel length (L/min)]					
State	Wet	Completely dry	Damp	Completely dry	Completely dry
Rating	7	15	10	15	15

to be reinforced by rock bolting. Nevertheless, it should be noticed that higher RSF values mean a greater load affecting the rock bolts, requiring an enhanced rock bolting efficiency. This idea was used in the Alborz Tunnel of Iran to determine whether to install rock bolts or shotcrete in cases where there was a necessity to proceed with the next round of excavation without completing the support system, as described in the RMR system, to achieve the monthly advance rate. It should be noticed that the type of rock bolts implemented is not a key factor as long as the design is properly carried out since the RSF is an intrinsic property of a rock mass and depends on the condition of discontinuities rather than the type of rock bolts. Figure 1 shows the relationship between RMR and RSF for different rock types presented in Table 7. As is obvious, RSF generally decreases with increased RMR values.

Mechanism of rock bolting

The mechanism of rock bolting has not been fully understood due to the existence of many varying properties of bolts and rocks. Four cases were studied by Habenicht (1983) in order to explain some of the important bearing capacity mechanisms of rock bolting; the cases are summarized as suspending, nailing, beam building and arch building effects. These effects are shown in Fig. 2. A designed rock bolting system must meet certain requirements on the basis of at least one of the aforementioned four effects. However, sometimes in cases with complex conditions, more than one effect is considered.

Benefiting from the concept of reinforcement by rock bolting, a fifth principle of bolting can be introduced. As mentioned in previous sections, the principle is very

Table 5 Different combinations of parameters to yield the basic RMR value of 45

State Parameter	A RMR = 45	B RMR = 45	C RMR = 45	D RMR = 45	E RMR = 45	F RMR = 45
UCS (Mpa)						
Value	68	80	110	140	260	80
Rating	7	8	10	12	15	8
RQD (%)						
Value	30	30	40	40	60	95
Rating	7	7	8	8	12	19
Spacing (mm)						
Value	50	50	100	200	200	500
Rating	6	6	8	8	8	11
Condition of discontinuities						
Persistence						
Value	1–3 m	3–10 m	10–20 m	10–20 m	>20 m	Soft gouge >5 mm thick
Rating	4	2	1	1	0	or
Aperture						
Value	0.1–1 mm	0.1–1 mm	0.1–1 mm	1–5 mm	>5 mm	Separation >5 mm
Rating	4	4	4	1	0	continuous
Roughness						
State	Very rough	Slightly rough	Smooth	Smooth	Slickensided	
Rating	6	3	1	1	0	
Infilling						
Value	None	None	None	None	None	
Rating	6	6	6	6	6	
Weathering						
State	Slightly weathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating	5	5	3	1	0	0
Groundwater [inflow per 10 meter tunnel length (L/min)]						
State	Flowing	Dripping	Dripping	Wet	Dripping	Wet
Rating	0	4	4	7	4	7

simple: rock bolting increases the discontinuity rating to its maximum in the RMR system, whereby it can be supposed that the RMR value of a rock mass also increases. Therefore, after rock bolting, the behavior of a complex of rock masses and bolts can be assumed as a new rock mass with the increased RMR value based on the rock bolting capability of the original rock mass. The RMR value of the complex of rock masses and bolts is the fifth rock bolting effect which is going to be mentioned as 'equivalent RMR' or 'RMR_{eq}'. The amount of increase in the RMR value to obtain the equivalent RMR is simply computed using Eq. 5.

$$\text{RMR}_{\text{eq}} - \text{RMR} = 30 - r_{\text{co}} \quad (5)$$

To formulate the fifth principle of rock bolting, the RSF is used in order to gain RMR_{eq}, as shown in Eq. 6, which can easily be concluded from Eqs. 5 and 3.

$$\text{RMR}_{\text{eq}} = \text{RMR} + 0.3\text{RSF} \quad (6)$$

Equation 6 is the mathematical definition of the fifth rock bolting principle, the importance of which is due to its form as a mathematical equation rather than simply being in an explanatory form. It should be noticed that any decimal value obtained for RMR_{eq} should be rounded up to give the exact value of RMR_{eq} as the mathematical [] sign was used to obtain the value of RSF. For instance, the obtained value for RMR_{eq} of state B in Table 3 is 89.8 which must be rounded up to yield the value of 90 for an equivalent RMR value.

RSF and the Q-system

The Q-system uses only two joint condition parameters, namely joint roughness (J_r) and joint alteration (J_a). The quotient of these parameters (J_r/J_a) represents the roughness and frictional characteristics of joint walls or filling

Table 6 Different combinations of parameters to yield the basic RMR value of 25

State Parameter	A RMR = 25	B RMR = 25	C RMR = 25	D RMR = 25	E RMR = 25
UCS (Mpa)					
Value	20	20	20	20	55
Rating	3	3	3	3	6
RQD (%)					
Value	10	20	10	10	10
Rating	4	5	4	4	4
Spacing (mm)					
Value	30	50	30	30	30
Rating	5	6	5	5	5
Condition of discontinuities					
Persistence					
Value	3–10 m	>20 m	10–20 m	>20 m	Soft gouge >5 mm thick or Separation >5 mm continuous
Rating	2	0	1	0	
Aperture					
Value	1–5 mm	1–5 mm	1–5 mm	>5 mm	
Rating	1	1	1	0	
Roughness					
State	Smooth	Smooth	Slickensided	Slickensided	
Rating	1	1	0	0	
Infilling					
Value	None	None	None	None	
Rating	6	6	6	6	
Weathering					
State	Moderately weathered	Moderately weathered	Highly weathered	Decomposed	
Rating	3	3	1	0	0
Groundwater [inflow per 10 meter tunnel length (L/min)]					
State	Flowing	Flowing	Dripping	Wet	Damp
Rating	0	0	4	7	10

Table 7 RSF values for different rock types of Tables 3, 4, 5 and 6

State	A	B	C	D	E	F
Rock types presented in Table 3						
RMR	85	85	85	85	–	–
RSF	0	16	33	50	–	–
Rock types presented in Table 4						
RMR	74	74	74	74	74	–
RSF	0	23	46	66	80	–
Rock types presented in Table 5						
RMR	45	45	45	45	45	45
RSF	16	33	50	66	80	100
Rock types presented in Table 6						
RMR	25	25	25	25	25	–
RSF	56	63	70	80	100	–

material. To define the rock bolting capability of a rock mass using the Q-system, these two parameters must be employed. Based on the Q-system, the J_r values differ from

0.5 to 4 for different discontinuity conditions, whereas the J_a values range from 0.75 to 20. Therefore, the values of the quotient J_r/J_a will range from 0.025 to 5.33. It can be

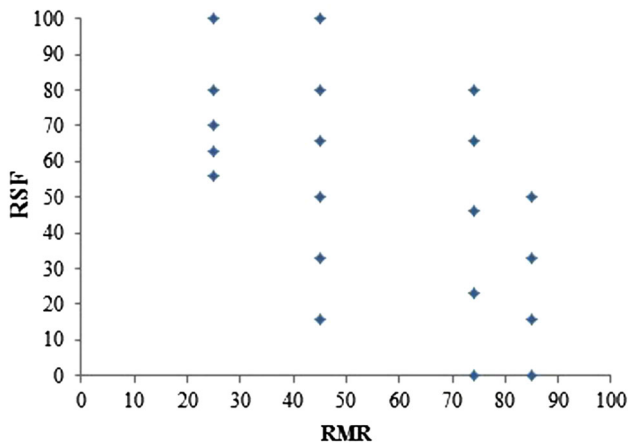


Fig. 1 RSF vs. RMR

assumed that the proper design and installation of a rock bolting system increases the value of this quotient from its initial value to its maximum of 5.33. Therefore, the amount of increase in the frictional characteristics of discontinuities (I_{fc}) can be calculated simply by using Eq. 7.

$$I_{fc} = 5.33 - \frac{J_r}{J_a} \tag{7}$$

As presented in Eq. 8, the percent of reinforcement obtained by rock bolting can be computed. In order to be in accordance with the values of Q-system, the results have

been multiplied by 1000. The QRSF values range from 4.71 to 1004.71.

$$QRSF = 1000 \times \frac{I_{fc}}{5.305} \tag{8}$$

A value of 5.305 is obtained from the difference of maximum and minimum values of the quotient J_r/J_a ($5.33 - 0.025 = 5.305$). Equation 8 can be rewritten as Eq. 9.

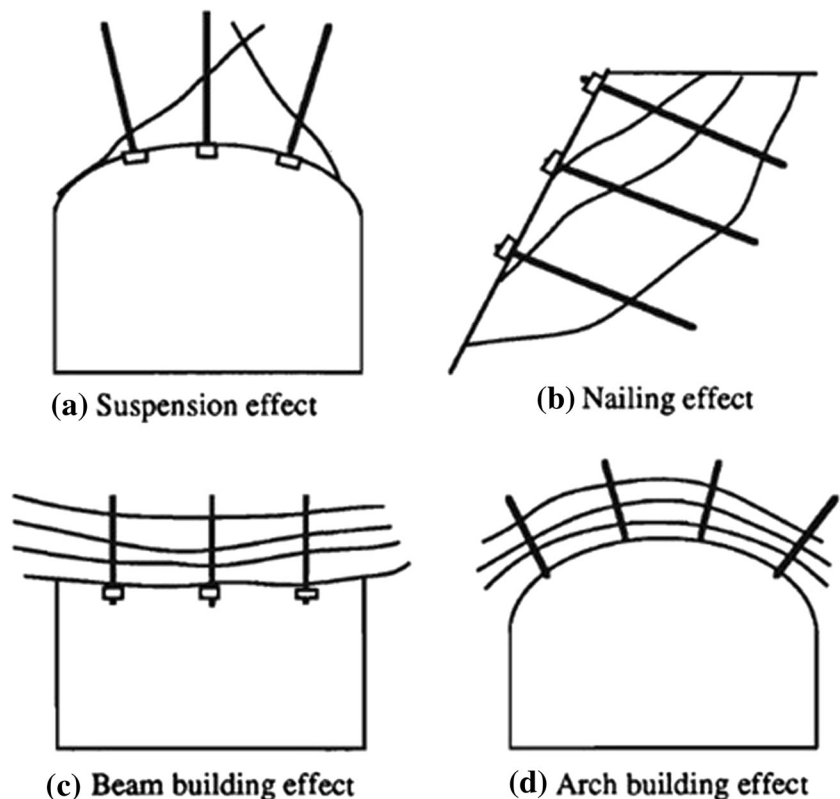
$$QRSF = 188.5 \times I_{fc} \tag{9}$$

Assuming that the proper design and implementation of the rock bolting system causes the Q value of rock mass to increase, the obtained value of Q for the combination of rock mass and rock bolting system (equivalent Q) can be calculated using Eq. 10, which is easily derived from Eqs. 2, 7, 8 and 9.

$$Q_{eq} = \frac{5.33 \times Q}{5.33 - \frac{QRSF}{188.5}} \tag{10}$$

The basic RMR and Q values in the Park River tunnel, as mentioned by Bieniawski (1989), were 56 and 9, respectively, where the overall rating of discontinuities for the RMR system was 25. The joints were rough, planar, unaltered walls with staining to which J_r and J_a values of 1.5 and 1, respectively, were allocated. The RSF value for this rock mass would be 16 whereas the QRSF value will be 722. As is obvious from the RSF value, the capability of

Fig. 2 Bolting principles (after Larsson 1984)



this rock mass to be reinforced by rock bolting is rather low. However, the QRSF value suggests a rather high capacity for the rock mass to be reinforced by rock bolting. Thus, the QRSF value demonstrates an inability to generate an accurate assessment of the rock bolting capability of a rock mass. This is because the Q-system and, subsequently, the QRSF equation, use only two parameters of discontinuity conditions, which leads to a poorer assessment of the rock bolting capability of a rock mass. The equivalent RMR and Q for this rock mass are 61 and 32, respectively. Therefore, the rock bolting practice upgraded the rock mass condition from fair to good in both systems. However, the QRSF leads to poorer assessments of the rock bolting capability of a rock mass.

Conclusions

Based on the condition of discontinuities in the RMR system, an equation was developed to compute the capability of a given rock mass to be reinforced by a rock bolting system. Using the RSF, a mathematical approach was introduced to explain the mechanism of rock bolting as a new principle.

Finally, a similar approach was developed based on the Q-system which has been named QRSF. The RSF proved to be more reliable than the QRSF in assessing the rock bolting capability of a rock mass by employing five parameters of discontinuity conditions rather than two parameters in the QRSF.

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