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Research Article

An Improved Method for Estimating the Strength of Jointed Rock Mass Using Drilling Technology

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During underground excavations for civil and mining engineering purposes, the variations in mechanical properties of jointed rock mass are important, especially for the design of underground structures. The unreasonable evaluation of strength properties for rock masses can lead to the structure instability of underground construct, which subsequently causes collapse accidents in underground engineering and poses a serious threat to the structures safety. Rock mass classification system is an effective method for determining the strength parameters for rock masses. Firstly, the existing approaches for determining the strength parameters of rock masses are reviewed using classification systems such as the joint factor, jointing index methods, rock mass rating (RMR), Q-system (Q), geological strength index (GSI), and rock quality designation (RQD). Since in some cases, rock quality designation (RQD) is the only information available, a comparative study with other methods then is conducted to verify the limitation and deficiencies of RQD method. On this basis, a newly developed method from RQD classification system based on drilling special energy is established to estimate the rock mass strength. Finally, the developed method is applied in the tunnel engineering in the Daheba hydropower station in Hanjiang to the Weihe River project of China, and the results are compared with those from the previous works. The in situ test results show that the developed method can give appropriate values compared to various suggested relationships from RMR, Q, and GSI. The results can be treated as an important design reference for the prevention and treatment of surrounding rock instability and underground excavations in the Daheba hydropower station.

1. Introduction

The design of underground structures in rock mass relies significantly upon reliable and accurate determination of normally the strength and deformation parameters. For typical dimensions of petroleum and gas storage systems, mine openings, water conveyance tunnels, underground powerhouse and chambers, etc., rock mass material is a composite material, which is made up of rock blocks separated by various joints.

Whereas rock stresses can be measured indirectly using measurements of strain for a stress relieved rock volume, or normal stress on a pressurized fracture, the rock mass strength cannot be measured at all [1]. The strength parameters of joints and rock can be assessed by laboratory work. However, the interaction between the rock and the joint, as well as the scaling rules in rock [2] and scale-dependent of fracture [3], is very complex and less well understood, hence making it hugely difficult to determine the strength parameters of rock mass from test results on small-scale rock. Although a variety of site tests such as block shear, plate loading, or flat jacking testing can provide only information on the parameters [4, 5], the tests are very high costly and practically difficult, especially in underground engineering, and can never be a good option [6].

Natural rocks are different from other engineering materials in that it contains discontinuous fracturing which render its structure macroscopic discontinuity and heterogeneity [7]. Large deformation, which can produce strong rock block motion and a fault slips, is associated with a remarkable increase in rock fracturing at seismic and huge engineering excavation [8]. Since laboratory experiments [9–13] have investigated the underlying deformation mechanisms of enhancement of fracturing on small jointed specimens, but it does not seem possible to predict accurately the deformability of rock masses due to the scaling rules in rock [14] and scale-dependent of fracture [15], in situ tests provide direct information on deformability at very high cost and time-consuming [16], also simply treating the jointed rock as an equivalent continuum [8]. Since laboratory experiments [2, 3, 9–13, 17–20], all kinds of empirical correlations have been proposed for the determination of deformability based on rock quality designation (RQD) [3, 21–24], rock mass rating (RMR) [23, 25–31], and geological strength index (GSI) [32–35]. Although various deformation mechanisms—such as joint density, joint orientation, joint spacing, and broken pieces—have been investigated, all of them seem to be triggered by macroscopic heterogeneity caused by fracturing.

The uncertainty variations in the strength of rock mass have an impact on the actual design of underground engineering [36]. A reliable and accurate strength determination, as well as a well understanding of the properties of rock mass, enables to reduce stability problems and waste rock extraction in underground design. The common approach for estimating the rock mass strength is as follows [1]: (i) mathematical modeling, (ii) back-analysis, (iii) large-scale testing, and (iv) rock mass classifications. A review of the five approaches to determine the rock mass strength including the advantage and limitation of each of these methods is presented by Edelbro [37]. Notably, some classification systems, such as RQD [16, 21, 22, 24], RMR [23, 25, 26, 28, 38, 39], Q [29–31], and GSI [32–35], have been developed to qualitatively assess the rock mass properties. Various empirical methods have been developed using RQD, GSI, RMR, and Q classification systems [7, 21, 26, 28, 29, 33, 40–47]. Although none of the empirical relations is absolutely the most reasonable and appropriate at a variety of fields with various rock types and site conditions, we may combine with some properties of rock mass to improve the methods. The disadvantages of these improved empirical methods may be removed to estimate the strength properties at very low cost and easily. The greatest advantage of these methods is, especially RQD method, their versatility, ease-of-use, and the simplest and quickest alternatives, which has led to their widespread. However, more practical and easy method is developed for determining the rock mass strength [1].

In this paper, an empirical method is modified for determining rock mass strength using rock drilling properties from RQD. The detailed field investigation is carried out at a tunnel engineering of rock mass. The modified relation is applied to determine the strength of rock masses in the surrounding rock instability and underground excavations in the Daheba hydropower station. The results are compared quantitatively with those from the different selected estimation methods.

2. The Strength of Jointed Rock Masses

Currently, there are various types of empirical relations such as joint methods and classification systems for estimating the strength properties of jointed rock mass. A review of these methods is carried out.

2.1. Jointing Index Methods. Jointing index methods are based on the ratio of whole length to fracture spacing or rock blocks number. Many researchers have established various methods of strength ratio ($\sigma_{\mathrm{cm}}/\sigma_c$) versus jointing index (L/l) from laboratory tests [48, 49]. Typically, the empirical $\sigma_{\mathrm{cm}}/\sigma_c$ versus L/l relations based on the results of uniaxial compression tests was suggested by Goldstein et al. [48]:

$$\frac{\sigma_{\mathrm{cm}}}{\sigma_c} = a + (1-a)\left(\frac{L}{l}\right)^{-e}, \tag{1}$$

where L is the sample whole length, σ_{cm} is the strength of jointed rock mass, σ_c is the strength of intact rock, and l is the discontinuity spacing. Figure 1 shows the variation of $\sigma_{\mathrm{cm}}/\sigma_{\mathrm{c}}$ with L/l for a and e different values. When there are more discontinuities in the length L, the strength decreases with an increasing in the value of L/l (Figure 1). The values of a and e mainly depend on the orientation and strength of the discontinuities [29, 50, 51]. Joint factor is very important for the description of correlation between the parameters and the geological data. The equations are very simple and give a fair estimating for the strength properties of jointed rock mass in the absence of reliable experimental data. For confining pressures other than zero, the statistical relationships may not always give a very good estimation of jointed rock as the database used in the statistical analysis [50, 51].

2.2. Joint Factor Methods. The joint factor methods are mainly dependent on the strength ratio $\sigma_{\mathrm{cm}}/\sigma_c$ with a joint factor including joint frequency, orientation, and strength [51–53]. According to the various results of intact and jointed rocks, the empirical relation of strength ratio $\sigma_{\mathrm{cm}}/\sigma_c$ versus joint factor J_f was proposed by Ramamurthy [52] and Arora [53].

$$\frac{\sigma_{\mathrm{cm}}}{\sigma_c} = \exp\left(-0.008 J_f\right), \tag{2}$$

where σ_{cm} is the unconfined compressive strength of rock mass and σ_c is unconfined compressive strength of intact rock. Based on the detailed statistical analysis of the expanded database [51] as shown in Figure 2, the best empirical correlation between $\sigma_{\mathrm{cm}}/\sigma_c$ and joint factor J_f was proposed by Jade and Sitharam [51].

$$\frac{\sigma_{\mathrm{cm}}}{\sigma_c} = a + b\exp\left(\frac{-J_f}{c}\right). \tag{3}$$

Notably, Equation (2) is a special form of Equation (3) with $a = 0$, $b = 1$, and $c = 25$. There is a great scatter for the obtained data. An estimation value from Equation (2) is possibly more or less than the measured value of σ_{cm}. It is worth noting that it is very possible that an estimation value from Equation (3) is more than two times or less than half of the measured value of σ_{cm} [52].

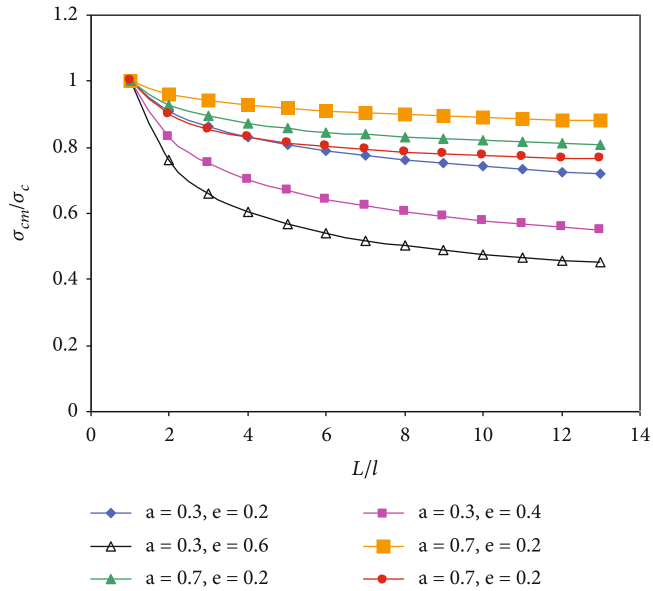


Figure 1: Variation of $\sigma_{\mathrm{cm}}/\sigma_{\mathrm{c}}$ with L/l for different a and e values.

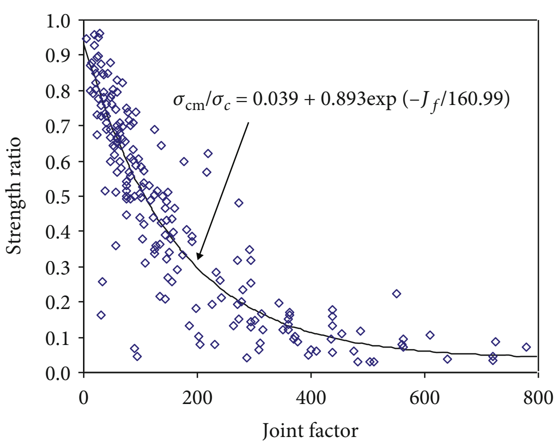


Figure 2: Strength ratio data and fitted relationship between $\sigma_{\mathrm{cm}}/\sigma_c$ and J_f [51].

2.3. Strength from Rock Mass Classification. Over the past many decades, a variety of classification systems for rock mass have been established by so many scholars. The most well-known many systems have been applied to engineering practice of rock mass, such as the RQD [21], RMR [54, 55], Q [30, 56], GSI [19, 57], RMi [58, 59], MRMR [60], and N [61]. Table 1 shows the parameters considered in different rock mass classification systems. All the systems tend to utilize the physical properties of rock mass using either quantitative or qualitative methods in rock engineering. Undoubtedly, the properties are the indispensable requirements for numerical modeling and engineering design. However, none of the classification systems could use all of the properties of rock mass and are absolutely the most reasonable and appropriate at a variety of fields due to the rock types and lack of homogeneity and isotropy. The properties of a particular rock mass could depend on the site variety, perhaps due to some differences in engineering judgments, characteristics, and site environment, which result in the creation and development of various classification systems for rock mass. A review of the various classification systems has been performed in Rehman et al. [36] and Edelbro [37].

As a variety of classification systems of rock mass were being proposed and developed, a problem arose: how to use the different classification systems in the different sites. Certainly, a correlation between the rock mass classification systems is established to calculate one from another in order to solve this problem. A variety of scholars have tried to approximately correlate the rock mass classification systems as listed in Table 2.

Many scholars have applied the classification systems of rock mass for the determination of rock masses strength [1, 26, 28, 29, 33, 40, 42–44, 46, 50, 60, 62–65]. The various relations based on the classification systems, GSI, Q, and RMR, are shown in Table 3, for estimating the strength of rock masses. It is worth noting that when using a classification system to assess the strength properties of rock masses, only the inherent properties of discontinuities and rock should be considered for determining the rock mass classification. Other properties such as in situ stress and groundwater need not be considered due to being considered in rock structures [24].

3. A Modified Method Based on RQD

After each experiment, we found indications of response to drill energy on rock fracturing (Figure 3). The drill energy from the “a single fracture in marble” plotted with the increasing of borehole depth in length range of f_2 is more scattered, since the presence of fracture pieces, than that those in intact marble, is observed in length range of f_1 and f_3 (Figure 3(a)). Fragmentation causes the drilling energy to drop into the void, as shown by the length region k_2, and then drop rapidly to almost zero, back to

Table 1: Parameters to consider for the different classification systems [37].

Classification systems	RMR	Q	GSI	RMI
Parameters	UCS	Joint set number	UCS	UCS
	RQD	RQD	Surface condition	Block volume
	Joint spacing	Joint roughness		Joint roughness
	Joint condition	Joint alternation	Structure/interlocking of rock blocks	Joint alternation
	Ground water condition	Joint water reduction factor		Joint size and termination
		Stress reduction factor		
Adjustment parameters	Joint orientation			

Table 2: Comparison of various correlation among the rock mass classification [4].

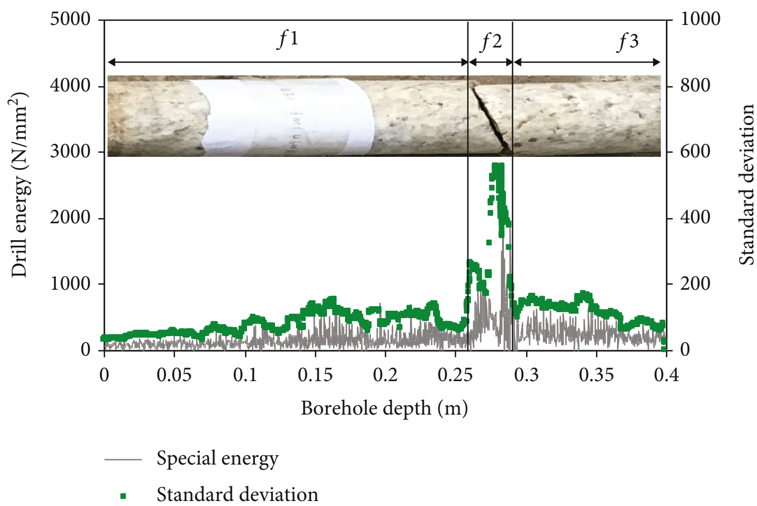
Researchers	Correlation	Estimated parameter
Bieniawski [54]	RMR = 9lnQ + 44	RMR from Q
Rutledge and Preston [69]	RMR = 5.9lnQ + 43	RMR from Q
Moreno [70]	RMR = 5.4lnQ + 55.2	RMR from Q
Cameron-Clarke and Budavari [71]	RMR = 5lnQ + 60.8	RMR from Q
Abad et al. [72]	RMR = 10.5lnQ + 41.8	RMR from Q
Kaiser and Gale [73]	RMR = 8.7lnQ + 38	RMR from Q
Al-Harthi [74]	RMR = 9lnQ + 49	RMR from Q
Barton [75]	RMR = 15lnQ + 50	RMR from Q
Tugrul [76]	RMR = 7lnQ + 36	RMR from Q
Kumar et al. [77]	RMR = 6.4lnQ + 49.6	RMR from Q
	RMR = 5.4lnRMi + 54.4	RMR from RMi
	$\mathrm{RMi} = 0.5\mathrm{Q}^{0.93}$	RMi from Q
	$\mathrm{RMR} = 1.5\ln\mathrm{Q}^{0.72}$	RMi from Q

Table 3: Empirical relations from the classification systems of RQD, RMR, Q, and GSI for determining unconfined compressive strength.

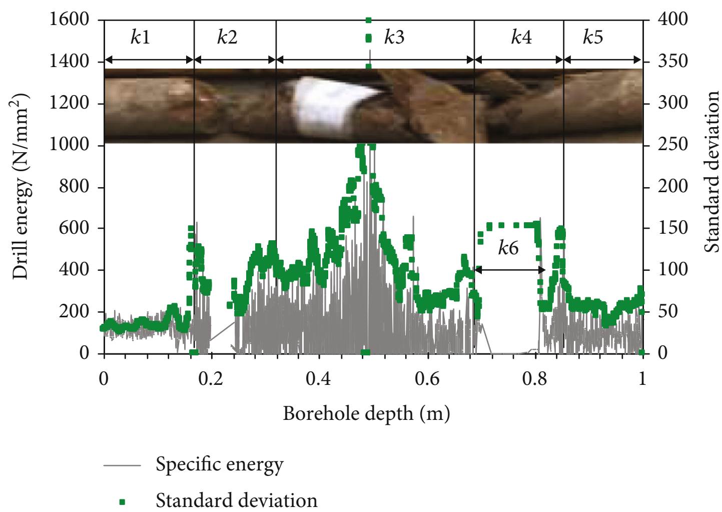
Authors	Relation	Equation
Yudhbir and Prinzl [26]	$\sigma_{\mathrm{cm}}/\sigma_c = e^{(7.65(\mathrm{RMR}-100))/100}$	(4)
Ramamurthy et al. and Ramamurthy [43, 44]	$\sigma_{\mathrm{cm}}/\sigma_c = e^{\mathrm{RMR}-100/18.75}$	(5)
Trueman [46]; Asef et al. [63]	$\sigma_{\mathrm{cm}} = 0.5e^{0.06\mathrm{RMR}}$	(6)
Kalamaras and Bieniawski [40]	$\sigma_{\mathrm{cm}}/\sigma_c = e^{\mathrm{RMR}-100/24}$	(7)
Hoek et al. [42]	$\sigma_{\mathrm{cm}}/\sigma_c = e^{(\mathrm{GSI}-100)/(9-3D)\left[(1/2)+(1/6)\left(e^{\mathrm{GSI}/15}-e^{-20/3}\right)\right]}$	(8)
Bhasin and Grimstad [45]; Singh and Goel [47]	$\sigma_{\mathrm{cm}} = 7\gamma f_c \mathrm{Q}^{1/3}$	(9)
Sheory [28]	$\sigma_{\mathrm{cm}}/\sigma_c = e^{\mathrm{RMR}-100/20}$	(10)
Aydan and Dalgic [29]	$\sigma_{\mathrm{cm}}/\sigma_c = \mathrm{RMR}/\mathrm{RMR} + 6(100\text{-}\mathrm{RMR})$	(11)
Barton [30]	$\sigma_{\mathrm{cm}} = 5\gamma(Q\sigma_c/100)^{1/3}$	(12)
Hoek [33]	$\sigma_{\mathrm{cm}}/\sigma_c = 0.036e^{\mathrm{GSI}/30}$	(13)
Singh et al. [41]	$\sigma_{\mathrm{cm}} = 7\gamma Q^{1/3}$	(14)
Zhang [24]	$\sigma_{\mathrm{cm}}/\sigma_c = 10^{0.013\mathrm{RQD}-1.34}$	(15)

prefragmentation levels (Figure 3(b)). In contrast, drilling energy variations along lengths k_3 and k_4 were observed in and after the fault zone (Figure 3(b)). Due to the heterogeneity of the rock, the effect of drill energy in drilling is related to the fracture of the rock [66].

The gap corresponds to the inhomogeneity (standard deviation) of the well over different lengths. The difference between the broken drilling energy and the standard deviation of intact rock as a function of drilling depth determines the difference in standard deviation as drilling



(a)



(b)

FIGURE 3: The distributions of fracture, specific energy, and standard deviation in each length range. (a) The core log, drilling energy, and standard deviation of drilling energy from the depths of 0 to 0.4 m in marble. Drilling energy and standard deviation correspond to a single fracture in marble was observed at the depth of 0.265~0.283 m. (b) The core log, drilling energy, and standard deviation of drilling energy from the depths of 0 to 1 m in limestone. Drilling energy and standard deviation correspond to fracture zones in limestone were observed at the depth of 0.0.185~0.831 m.

depth increases. The energy distribution of the crusher is more dispersed throughout the rock because the mechanical properties of the crusher are lower than those of the homogeneous part.

The relation between strength ratio σ_{cm}/σ_c and the modulus ratio E_m/E_r can be newly derived for determining the strength ratio from RQD [24]:

$$\frac{\sigma_{\mathrm{cm}}}{\sigma_c} = a_E^q = 10^{0.013\mathrm{RQD}-1.34}. \tag{4}$$

The developed relation by Zhang [24] from a nonlinear variation in Equation (4), which covers the entire range of RQD, using the σ_{cm}/σ_c versus E_m/E_r relationship of Ramamurthy [52], Singh et al. [67], and Singh and Rao [68] may be appropriate for deriving the σ_{cm}/σ_c, which was derived based only on test results from laboratory work [52, 67, 68], and the model parameters "0.013" and "1.34" may vary significantly for different discontinuity conditions and rock types.

Hence, we assume that the model parameters in Equation (4) "0.013" and "1.34" are dependent on rock types, the Equation (16) can be modified empirically as

$$\frac{\sigma_{\mathrm{cm}}}{\sigma_c} = a_\sigma = 10^{(\eta\mathrm{RQD}/100)-\eta}, \tag{5}$$

where σ_{cm} is the unconfined compressive strength of rock mass, σ_c is the unconfined compressive strength of intact rock, η is a parameter related to the unconfined compressive strength σ_c, deformation modulus E_r, and drilling energy e of intact rock [66], $\eta = eE_r/q\sigma_c$, q =20.

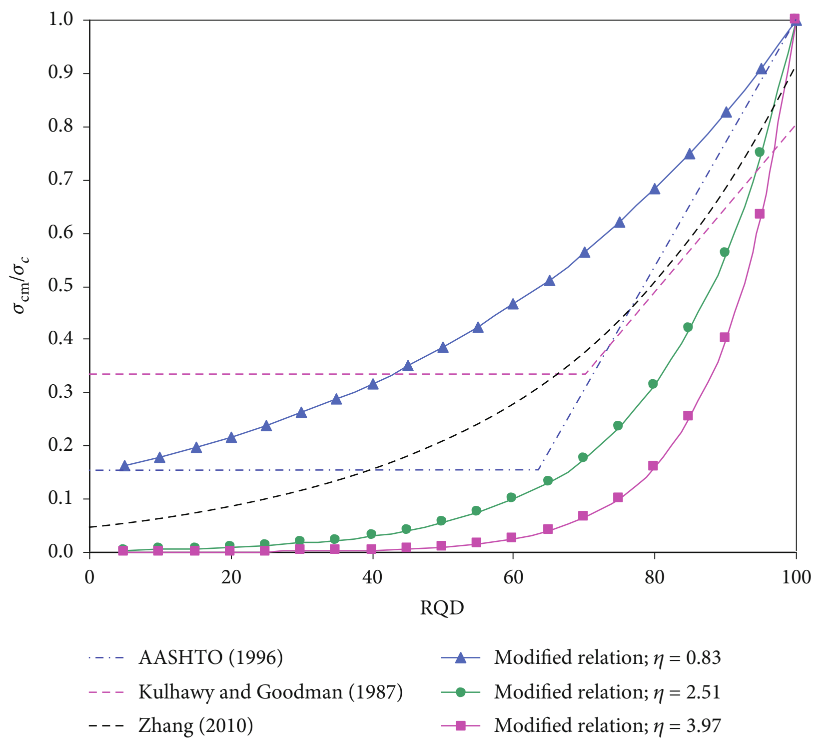


Figure 4: Comparison between the modified σ_{cm}/σ_c versus RQD relations and suggestions by Ramamurthy [52], Singh et al. [67], and Singh and Rao [68], respectively.

Table 4: Summary of rock properties at the site.

Segment no.	Rock	E_r (GPa)	σ_c (MPa)	e (N/mm^2)	RQD	RMR	Q	GSI
1	Limestone	13.8	74.6	271.3	93.50	81.90	8.39	63.14
2		13.8	74.6	271.3	65.40	74.50	5.12	58.70
3		13.8	74.6	271.3	70.50	76.24	5.75	59.74
4		13.8	74.6	271.3	78.20	79.65	7.22	61.79
5		13.8	74.6	271.3	75.30	77.94	6.44	60.76
6		13.8	74.6	271.3	45.20	65.71	2.85	53.43
7		13.8	74.6	271.3	91.50	81.62	8.23	62.97
8		13.8	74.6	271.3	88.60	77.56	6.28	60.54
9		13.8	74.6	271.3	93.50	82.22	8.57	63.33
10	Tuff	4.9	31	105.3	90.70	77.73	6.35	60.64
11		4.9	31	105.3	91.10	79.57	7.18	61.74
12	Marble	23.4	87	295.1	60.20	74.53	5.13	58.72
13		23.4	87	295.1	50.60	73.90	4.92	58.34
14		23.4	87	295.1	63.80	75.95	5.64	59.57

Figure 4 shows the comparison study of the modified method in Equation (5) from test data of tuff, limestone, and marble with the method, respectively, from Kulhawy and Goodman [62], AASHTO [64], and Zhang [24]. Equation (5) also covers the range of $0 < \text{RQD} < 100\%$. For $0 < \text{RQD} < 100$, Equation (17) is in good agreement with the range from Kulhawy and Goodman, AASHTO, and Zhang. However, Equation (5) is different from the suggestions of Kulhawy and Goodman [62], AASHTO [64], and Zhang [24] with the new σ_{cm}/σ_c versus RQD relation considering the variation of rock types, while the suggestions of Zhang [24] assume constant η values.

4. Comparative Analysis

To evaluate the application of the modified σ_{cm}/σ_c-RQD ratio in determining the strength of jointed rock mass, a field test was carried out on the right bank of the Hanjiang-Weihe project traffic tunnel. We conduct detailed field investigations such as field observations, inventories, structural

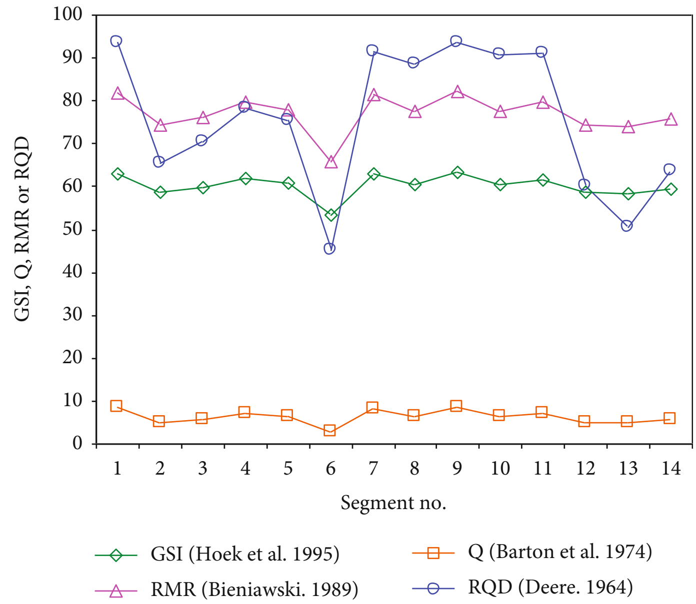


Figure 5: The rock mass classification for 14 segments passing rock formations using 4 systems: RMR, Q, RQD, and GSI.

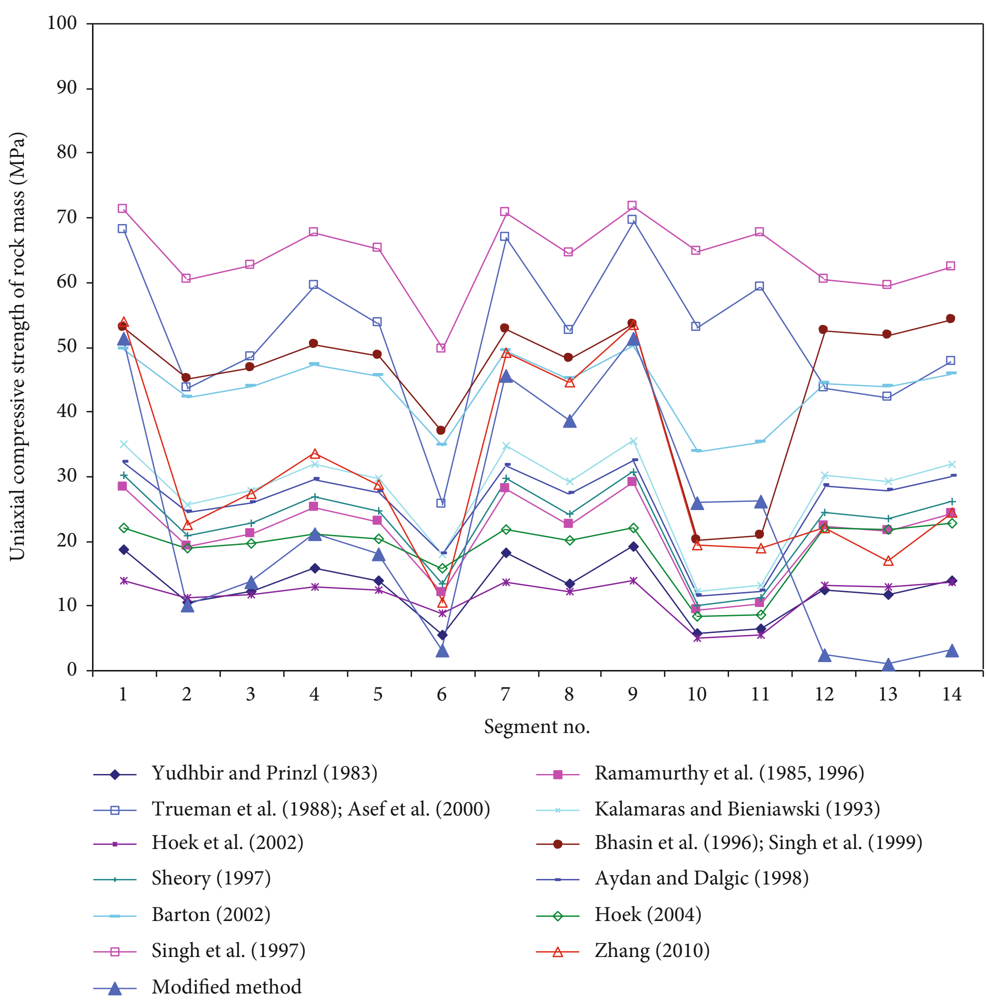


Figure 6: A comparative study of the developed relation with the estimated strength values from the previous empirical methods.

TABLE 5: Using the developed method Equation (17) and the previous relationship, the evaluated strength values of the weights listed in Table 4.

No.	Equation (4)	Equation (5)	Equation (6)	Equation (7)	Equation (8)	Equation (9)	σ_{cm} Equation (10)	Equation (11)	Equation (12)	Equation (13)	Equation (14)	Equation (15)	Equation (17)
1	18.7	28.4	68.1	35.1	13.9	53.0	30.2	32.1	49.8	22.0	71.1	54.0	51.2
2	10.6	19.1	43.7	25.8	11.3	45.0	20.8	24.4	42.2	19.0	60.3	22.5	10.1
3	12.1	21.0	48.5	27.7	11.8	46.8	22.7	26.0	43.9	19.7	62.7	27.4	13.6
4	15.7	25.2	59.5	32.0	13.0	50.5	27.0	29.5	47.3	21.1	67.6	33.6	21.2
5	13.8	23.0	53.7	29.8	12.4	48.6	24.8	27.6	45.6	20.4	65.1	28.7	17.9
6	5.4	12.0	25.8	17.9	8.8	37.0	13.4	18.1	34.7	15.9	49.6	10.5	3.1
7	18.3	28.0	66.9	34.7	13.8	52.7	29.8	31.7	49.4	21.9	70.7	49.3	45.7
8	13.4	22.5	52.5	29.3	12.3	48.2	24.3	27.3	45.2	20.2	64.6	44.6	38.6
9	19.1	28.9	69.4	35.6	14.0	53.4	30.7	32.5	50.1	22.2	71.6	53.4	51.2
10	5.6	9.5	53.0	12.3	5.1	20.1	10.2	11.4	33.8	8.4	64.8	19.4	25.9
11	6.5	10.4	59.2	13.2	5.4	20.9	11.2	12.2	35.3	8.7	67.5	19.0	26.1
12	12.4	22.4	43.7	30.1	13.2	52.5	24.3	28.5	44.5	22.2	60.4	22.1	2.3
13	11.8	21.6	42.1	29.3	12.9	51.8	23.6	27.9	43.8	21.9	59.5	16.9	1.0
14	13.8	24.1	47.6	31.9	13.7	54.2	26.1	30.0	45.9	22.8	62.3	24.5	3.2

surface measurements, rock classification, and laboratory testing. The results are compared to those based on various RQD, RMR, Q, and GSI relationships to provide an improved approach to Equation (5). The rock properties shown in Table 4 cover a reasonable but apparently limited range of rock types. The rock mass classification has been done for 14 segments using RMR, Q, GSI, and RQD systems (the RQD obtained by using drilling energy in this paper) (Table 4). Figure 5 shows the calculation results of various empirical relations from RQD, RMR, Q, and GSI systems for the estimation of rock masses strength, respectively.

Figure 6 shows the ratio $\sigma_{\mathrm{cm}}/\sigma_{\mathrm{c}}$ and strength σ_{cm} corrected for RQD (Equation (5)) according to different empirical relationships between Q, RMR, GSI, and RQD. The modified ratio values actually fall within a range of different relational values based on Q, RMR, GSI, and RQD. A report by Singh et al. [41] and Trueman [46] tends to estimate high values of σ_{cm}, but Yudhbir and Prinzl [26] and Hoek et al. [42] tend to estimate low values of σ_{cm}. Some correlations proposed by other researchers [28–30, 33, 43, 47, 61, 63, 64] give the mean value of σ_{cm}. Furthermore, the σ_{cm} value estimated by the modified bond is slightly higher than that estimated by Zhang's method [24] (Table 5).

For segment no. 1 and 7~11, as compared to other segment, RQD presents high values (about >90) and evaluates the rock mass similarly to the RMR and GSI description as shown in Figure 4, probably due to less fractures and broken pieces in the segments. In addition, according to the classification of RMR, Q, and GSI, the intensity values of each segment obtained from the corrected relationship between $\sigma_{\mathrm{cm}}/\sigma_c$ and RQD are in the middle of the value ranges of different relationships. However, although there are similar RQD values, the strength values along segments of 10 and 11 from the modified relation are slightly lower than those along segments of 1 and 7~9 for limestone mass (Table 5), due to the high η value in Equation (5), which are quantitative reflection to low strength, deformation modulus, and drilling energy of intact tuff.

Along segment no. 2~5, 12, and 14, RQD presents slight high values ($60 < \mathrm{RQD} < 80$, Figure (5)) due to moderate fractures and broken pieces in the segments. The modified $\sigma_{\mathrm{cm}}/\sigma_c$ versus RQD relation tends to estimate lower strength value (in lower bound) in the segments compared to the estimated values from the different relations based on RMR, Q, and GSI classifications.

Along segment no. 6 and 13, there are more cracks, less agglomeration, and low RQD, Q, RMR, and GSI values. Of these two parts, RQD-based correction relationships tend to provide more conservative estimates for the strength of jointed rock mass than RMR, Q, and GSI systematic methods. Therefore, the relationship between the corrected $\sigma_{\mathrm{cm}}/\sigma_c$ and RQD can better determine the strength of jointed rock mass and is in good agreement with various dif-based relationships.

Determining the unconfined compressive strength of rock mass using is an indirect method using drilling parameters. Evaluating the strength properties of rock mass in the process of drilling is possible using the continuous measurement of drilling parameters. Beside the advantage of continues measuring, this method can be usually applied as a quasi-nondestructive technology in field. In large scale, the drilling method can be easily performed owing to the low cost and no need for sampling.

5. Conclusions

In many cases, scale quality determination (RQD) is the only information on the rock texture grade, so we vary the ratio of $\sigma_{\mathrm{cm}}/\sigma_c$ to RQD to determine scale strength from scale properties. The correction link is the determination for the strength of jointed rock mass at Weihe-Hanjiang Daheba hydropower station. The results were quantitatively compared with different evaluation methods.

(1) The $\sigma_{\mathrm{cm}}/\sigma_c$ versus RQD relation is modified using rock properties that provide the moderate estimation of rock mass strength that often corresponds with those from the previous methods

(2) The modified method of the strength of jointed rock mass estimation tends to give low (conservative) values at low RQD values and intermediate values of RMR, Q, and GSI at high RQD values

(3) The modified methods provide a convenient way for estimating rock masses strength, but they should be used together with the previous methods, and the limitations need to be considered

Data Availability

Data will be available on request. Yong Zhang is contacted to request the data (E-mail: 2605703687@qq.com).

Conflicts of Interest

The authors declare no conflict of interest.

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