International Journal of Rock Mechanics and Mining Sciences 108 (2018) 96–104

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Improving the Hoek–Brown criterion based on the disturbance factor and geological strength index quantification

Wenkai Feng[a], Shan Dong[b,*], Qi Wang[b], Xiaoyu Yi[b], Zhigang Liu[b], Huilin Bai[b]

[a] State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (Chengdu University of Technology), Chengdu 610059, China
[b] Chengdu University of Technology, Chengdu 610059, China

ARTICLE INFO

Keywords:
Hoek–Brown criterion
Disturbance factor
Geological strength index quantification
Surface condition rating
Structure plane condition factor
Structure rating

ABSTRACT

A supplementary quantified approach for the GSI system is proposed by focusing on improving the GSI and the rock mass disturbance factor (*D*). The surface condition rating (*SCR*), the structure plane condition factor (J_c), the rock mass basic quality index (*BQ*), and the rock mass structure rating (*SR*) are used in the proposed method. An improved formula for the disturbance factor (*D*) using the *BQ* is established. With this method, the GSI value is a set of possible numbers within given intervals rather than a constant value. The relationship between the GSI and rock mass D reflects not only the disturbance degree of the rock mass from the wave velocity but also the difference in the disturbance degree from the strength, which increases the accuracy of the D value. In addition, because of the value of the standard differences among the *SCR*, J_c, *BQ* and *SR*, the GSI region may be considerably wider due to quantification factors with larger differences. Thus, the method of measuring the interval value can maximize error reductions, and intermediate interval values are recommended for use.

1. Introduction

The mechanical behavior of cataclastic rocks is poorly understood because of difficulties associated with performing observations and analyses of these rocks from the surface, collecting samples during field investigations, preparing specimens and conducting laboratory testing.[1] Obtaining reliable estimates of rock mass strength and stiffness are critical when performing a geotechnical analysis.[2] Many parameters affect the deformability and strength of jointed rock mass; thus, developing a universal law that can be used in practical methods for predicting rock mass strength is generally impossible. Compared with other methods, in situ tests are relatively accurate and can directly obtain the mechanical parameters of cataclastic rock. However, these tests can only be performed when exploration adits are excavated; moreover, the cost of conducting in situ tests is high. For laboratory experiments, the experimental results could be significantly influenced by the dimensional effect. Because the mechanical properties of cataclastic rock can change, test results may not be stable when small perturbations occur in laboratory tests. Over time, many classification systems, such as the RQD system, rock mass rating (RMR) system, Q system and geological strength index (GSI) system, have been developed. Among them, the GSI system is used for estimating design parameters.[3] Hoek et al. developed the GSI, which can estimate rock mass deformability and strength.[4] In 2002, Hoek and Brown presented a new method of GSI parameter selection and introduced the disturbance parameter *D*.[5] The method for estimating the GSI proposed by Hoek uses two main parameters: rock mass structure and structure plane features. Both parameters rely on a qualitative description and a lack of concrete quantization parameters. The accuracy of this method depends mostly on the engineer's experience and judgment with strong subjective factors; thus, the structural parameters of a rock mass are difficult to quickly and accurately determine.[6]

In this paper, a new method for determining the mechanical parameters of a rock mass is proposed based on the improved Hoek–Brown criterion. The surface condition rating (*SCR*), the structure plane condition factor (J_c), the rock mass basic quality index (*BQ*), and the rock mass Structure rating (*SR*) are used in the new method. An improved formula for the disturbance factor (*D*) using the *BQ* is established. The parameters obtained from laboratory tests are incorporated into the improved Hoek–Brown formulas used to calculate the physical and mechanical parameters of cataclastic rock mass in the bedding shear zone. In addition, borehole shear testing was performed in the bedding shear zone in the field, and the testing results are compared with the Hoek–Brown criterion and the results of the improved method.

* Corresponding author.
E-mail addresses: fengwenkai@cdut.edu.cn (W. Feng), dongshan1994@hotmail.com (S. Dong), 965067381@qq.com (Q. Wang), xiaou.geo@qq.com (X. Yi), 396492188@qq.com (Z. Liu), 553884932@qq.com (H. Bai).

https://doi.org/10.1016/j.ijrmms.2018.06.004
Received 16 May 2017; Received in revised form 1 May 2018; Accepted 6 June 2018

2. Improvement and application of the Hoek–Brown criterion

2.1. Hoek–Brown criterion

The Hoek-Brown criterion was originally developed to estimate the rock mass strength for a jointed rock mass based on estimates of blockiness and the surface condition of discontinuities.[7] The Hoek-–Brown rock criterion is based on the Griffith criterion of brittleness, which is a nonlinear empirical relationship for the limiting principal stress of rock failure.[5] The Hoek–Brown rock criterion is expressed as follows:

$$\sigma_1 = \sigma_3 + \sigma_c\left(m_i\frac{\sigma_3}{\sigma_c} + 1\right)^{0.5} \tag{1}$$

where σ_1 and σ_3 are the major and minor effective principal stresses at failure, respectively, σ_c is the uniaxial compressive strength of the intact rock material, and m_i is an empirical parameter.

The Hoek–Brown rock criterion is mainly intended for use on rock blocks with high cohesion and integrity; this criterion is not applicable to loose jointed rock masses. The modified Hoek–Brown criterion has been improved by Hoek et al. to expand its applicability. The additional empirical parameters of m_b and a, which are related to the rock properties, were proposed and the parameter of s, which represents the fracturing degree of the rock mass ranging from 0 to 1, was included to make the Hoek–Brown rock criterion suitable for use in rock masses.[8,9]

$$\sigma_1 = \sigma_3 + \sigma_c\left(m_b\frac{\sigma_3}{\sigma_c} + s\right)^{a} \tag{2}$$

Undisturbed rock mass:

$$m_b = \exp\left(\frac{RMR - 100}{28}\right)m_i \tag{3}$$

$$s = \exp\left(\frac{RMR - 100}{9}\right) \tag{4}$$

$$a = 0.5 \tag{5}$$

Disturbed rock:

$$m_b = \exp\left(\frac{RMR - 100}{14}\right)m_i \tag{6}$$

$$s = \exp\left(\frac{RMR - 100}{6}\right) \tag{7}$$

$$a = 0.5 \tag{8}$$

The Hoek-Brown criterion[5] is used to determine a yield surface for intact rock based on laboratory test results. Additionally, a new GSI parameter selection method introducing D is presented, which is a factor that depends on the degree of disturbance to which the rock mass has been subjected by blast damage and stress relaxation.

$$m_b = \exp\left(\frac{GSI - 100}{28 - 14D}\right)m_i \tag{9}$$

$$s = \exp\left(\frac{GSI - 100}{9 - 3D}\right) \tag{10}$$

$$a = \frac{1}{2} + \frac{1}{6}(e^{-GSI/15} - e^{-20/3}) \tag{11}$$

Parameters m_b, s, and a all depend on the GSI, which ranges from 5 (for a highly cataclastic, poor rock mass) to 100 (for an intact rock mass). The parameter m_i is the Hoek–Brown constant for intact rock, and its value (1.0–35.0) reflects the hardness of the rock mass. The value of D ranges from 0 (for an undisturbed rock mass) to 1 (for a disturbed rock mass)

When $\sigma_t < \sigma_3 < \sigma'_{3max}$, the formula for the rock mass shear-strength parameters C and φ can be obtained using Eqs. (12) and (13)[5]:

$$\varphi' = \sin\left[\frac{6am_b(s + m_b\sigma'_{3n})^{a-1}}{2(1 + a)(2 + a) + 6am_b(s + m_b\sigma'_{3n})^{a-1}}\right] \tag{12}$$

$$c' = \frac{\sigma_{ci}[(1 + 2a)s + (1 - a)m_b\sigma'_{3n}](s + m_b\sigma'_{3n})^{a-1}}{(1 + a)(2 + a)\sqrt{1 + (6am_b(s + m_b\sigma'_{3n})^{a-1})/(1 + a)(2 + a)}} \tag{13}$$

$$\sigma_{3n} = \frac{\sigma'_{3\,max}}{\sigma_{ci}} \tag{14}$$

Hoek et al. suggest determining the maximum confining level for a slope and deep tunnels using the following equations[5]:

$$\frac{\sigma'_{3\,max}}{\sigma'_{cm}} = 0.72\left(\frac{\sigma'_{cm}}{\gamma H}\right)^{-0.91} \tag{15}$$

$$\frac{\sigma'_{3\,max}}{\sigma'_{cm}} = 0.47\left(\frac{\sigma'_{cm}}{\gamma H}\right)^{-0.94} \tag{16}$$

where γ is the bulk density of the rock mass, h is the slope height or the embedded depth of a tunnel, and σ_{cm} is the compressive strength of the rock mass.

When $0 < \sigma_3 < 1/4\sigma_c$, the compressive strength of the rock mass σ_{cm} can be expressed as follows:

$$\sigma'_{cm} = \sigma_{ci}\frac{(m_b + 4s - a(m_b - 8s))(m_b/4 + s)^{a-1}}{2(1 + a)(2 + a)} \tag{17}$$

From the above analyses, the key to determining the mechanical parameters of a rock mass is to determine the quantified values of *GSI* and *D*.[5]

2.2. Improved method for calculating the geological strength index

2.2.1. Quantitative analysis of rock mass structure

Based on the rock mass structure and structure plane feature, we propose solutions to the issues discussed above. We combine the rock mass structure plane surface grade *SCR*, J_c, *BQ*, and *SR* to determine the value of the quantization parameter. The GSI value is presented as a set of possible numbers in certain intervals rather than a constant value.

Quantification of the structure plane characteristics**:** The rock mass structure plane surface grade *SCR* includes three factors: the infilling rating R_f, the weathering rating R_w, and the roughness rating R_r. The value of R_f, R_w and y are shown in Table 1. The formulae for *SCR* and J_c are as follows:

$$SCR = R_f + R_w + R_r \tag{18}$$

Table 1
SCR value table of the structural surface condition rating.[12]

Infilling rating (R_f)	Thickness	Value	Weathering rating (R_w)	Value	Roughness rating (R_r)	Value	SCR
None	/	6	Unweathered	6	Very rough	6	$R_f + R_w + R_r$
Hard	< 5 mm	4	Slightly weathered	5	Rough	5	
Hard	> 5 mm	2	Moderately weathered	3	Slightly rough	3	
Soft	< 5 mm	2	Highly weathered	1	Smooth	1	
Soft	> 5 mm	0	Decomposed	0	Slickenside	0	