IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 11, 2019, accepted September 10, 2019, date of publication September 16, 2019, date of current version October 11, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2941833

The Use of Hoek Brown Failure Criterion on Determination of the Geo-Mechanical Parameters of a Grouting Consolidation Body

LEI WEN, ZHOU QUAN LUO, YA GUANG QIN, AND ZHEN YAN LUO
School of Resources and Safety Engineering, Central South University, Changsha 410083, China

Corresponding authors: Zhou Quan Luo (lzq505@csu.edu.cn) and Ya Guang Qin (csuqyg@163.com)

This work was supported in part by the National Key Research and Development Program of China during the Thirteenth Five Year Plan Period: The Continuous Mining Theory and Technology on Spatiotemporal Synergism of Multi-mining Areas within a Large Ore Block for Deep Metal Deposit under Grant 2017YFC0602901, and in part by the Graduate Students Explore Innovative Projects Independently Program under Grant 2017zzts188.

ABSTRACT In this paper, the mechanical parameters of the grouting consolidation body on the rock block are studied using the Acoustic velocity test case and the revised Hoek-Brown failure criterion in underground metal mines. In light of the hidden resources in the collapsed area of the underground metal mine, the intact rock drilling core cannot be obtained to perform the mechanical test because of extreme damage or because it is completely broken. Therefore, pure cement grouting is used to reinforce the extremely broken rock mass within the collapsed area of the hidden resources. The RQD value and water permeability are tested to indicate that cement pastes can fill the cracks in broken rock blocks and can improve the integrity of the broken rock mass. To detect the grouting consolidation effect of the fractured rock mass and evaluate the mechanical parameters of the consolidation body, a nondestructive test is applied to measure the Acoustic velocity of the consolidation body after grouting. Initially, the measured Acoustic velocity is adopted to calculate the damage index (or integrity index), which is approximately equivalent to the disturbance factor. Then, the modified Hoek-Brown failure criterion is used to evaluate the mechanical parameters of the grouting consolidation body. Finally, to verify this method, the mechanical parameters of the rock mass are also obtained by a laboratory test. The outcomes show that the current research can serve as a practical method when evaluating rock mass quality by the grouting treatment.

INDEX TERMS Acoustic waves, civil engineering, consolidation body, Hoek Brown criteria, Young's modulus.

I. INTRODUCTION

In previous studies, the study or evaluation of the mechanical parameters of rock masses have been addressed using an empirical formula and a mechanical test. However, the most widely used criteria are those currently used in various engineering codes of different regions and countries, such as ASTM [1], [2], Engineering and Design–Rock Foundations [3], Rock Foundations [4], Standard Specifications for Highway Bridges [5], and the Canadian Foundation Engineering Manual [6]. Based on the different criterion that is used, the results computed differ considerably, although they are of the same order of magnitude. For intact rock, the Mohr–Coulomb criterion is the most used failure criterion. Singh *et al.* [7] took the non-linearity triaxial or polyaxial strength into account to modify this criterion. Furthermore, Singh M also discussed the application of a modified Mohr–Coulomb criterion in a jointed rock mass [8]. Li *et al.* [9] stated that the best way to solve rock mass problems is to employ the Hoek–Brown failure criterion. However, some studies [10]–[12] have stated that the general Mohr–Coulomb failure criterion is not appropriate for describing the damaged or fractured rock mass strength. When the rock mass has few fractures that could be regarded as being on the macro level, it is complete and continuous. In this case, there are studies that use the finite element method or software to simulate the opening operations of the rock mass and to estimate the rock slope's stability [13]–[17].

The associate editor coordinating the review of this manuscript and approving it for publication was Jiansong Liu.

A theoretical analysis of the mechanical characteristics in extremely damaged or fractured rock masses has barely been researched, mainly because they have inherent characteristics due to heterogeneity, anisotropy, discontinuities, etc. In light of these reasons, a simple linear failure criterion would be inaccurate or unrealistic. In this regard, the Hoek–Brown failure criterion, a non-linear empirical strength criterion for a rock mass and intact rock, was proposed by Hoek and Brown [18] and Hoek *et al.* [19], which is mostly used to estimate the strength of damaged or fractured rock masses, not only when solving excavation problems but also when determining the mechanical behavior of damaged or fractured rock masses. Some studies take the Hoek–Brown failure criterion into account to assess the stability of the rock slope. Li *et al.* [13] focused on producing the stability charts of rock slopes using a numerical limit analysis based on the Hoek–Brown failure criterion, which makes the difference in the safety factor between the limit equilibrium analyses and bound solutions less than 4%. Yang [20] attempted to use a modified Hoek–Brown failure criterion to study the seismic displacement of rock slopes under earthquake loading. Moreover, a modified or generalized Hoek–Brown failure criterion was also one widely accepted approach to estimating the ultimate bearing capacity of rock masses, such as Jing and Liu [21], Saada *et al.* [22], Merifield *et al.* [23], and Keshavarz *et al.* [24]. Nevertheless, few studies have focused on assessing the strength and other parameters of the grouting consolidation body by the Hoek–Brown failure criterion.

The study of grouting on rock masses has frequently appeared in the literature, such as in tunnels, mines, roads and other underground engineering supports structures. Only a few researchers have assessed the rock masses improvement due to cement grouting. Kikuchi *et al.* [25] attempted to take advantage of field rock mechanical experiments and geophysical methods to evaluate the grouting effects on the rock quality, such as the electromagnetic wave, elastic wave prediction and borehole expansion test. Numerical simulation models were conducted by Li and Wu [26] to assess the effects of grouting. Utsuki [27] performed dilatometer tests to examine the improvement of grouting and concluded that after grouting the deformation modulus is larger than before grouting. Zolfaghari *et al.* [28] employed a Q-system to evaluate the improvement in the rock mass improvement after grouting. Few researchers have evaluated the mechanical parameters of grouting consolidation. Thus, the main objective of this paper is to employ the modified Hoek–Brown failure criterion to calculate the mechanical parameters of the grouting consolidation body. This calculation method is obtained using the integrity index, which is a ratio in which the numerator is the velocity squared of the grouting consolidation body (the field acoustic velocity of the grouting area) and the denominator is the velocity squared of the intact rock mass, based on the generalized Hoek–Brown failure criterion. A comparative analysis is given, and the obtained results due to the modified Hoek–Brown failure criterion show a good rationality and reliability with the measured results. Thus, in this paper a novel application of the modified Hoek–Brown failure criterion is proposed to assess the rock masses mechanical characteristics improvement after performing grouting treatment.

II. REVISED HOEK-BROWN FAILURE CRITERION BASED ON ACOUSTIC VELOCITY

A. MODIFIED HOEK-BROWN FAILURE CRITERION

The Hoek–Brown failure criterion was first proposed in 1980 [29]. The criterion has since been frequently revised by Hoek [30]. The latest version of the Hoek–Brown failure criterion for rock mass is expressed as [19]:

$$\sigma_1 = \sigma_3 + \sigma_c \left(m \frac{\sigma_3}{\sigma_c} + s \right)^a \tag{1}$$

where the σ_c is uniaxial compressive strength of intact rock, the σ_1 is the maximum principal stress, the σ_3 is the minimum principal stress, the constants m, s and a can be expressed using the geological strength index (GSI), as follows:

$$\frac{m}{m_i} = \exp\left(\frac{GSI - 100}{28 - 14D} \right) \tag{2}$$

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

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-\frac{GSI}{15}} - e^{-\frac{20}{3}} \right) \tag{4}$$

The GSI was introduced because Bieniawski's rock mass rating (RMR) system [31] and the Q-system [33] were deemed to be unsuitable for poor rock masses. The GSI ranges from approximately 10 for extremely poor rock masses to 100 for intact rock. The parameter D is a factor that depends on the degree of disturbance. The suggested value of the disturbance factor is $D = 0$ for undisturbed in situ rock masses and $D = 1$ for disturbed rock mass properties.

For an extremely broken rock mass, there is an assumption that the grouting can effectively consolidate the broken rock mass. Thus, the grouting consolidation body is considered as a continuous medium from a macroscopic point of view. Considering the difference of the acoustic velocity between the pure cement paste consolidation body and intact rock, a nondestructive testing method is used to test the acoustic velocity of the grouting consolidation body. The integrity index of the consolidation body is stated as follows:

$$K_V = \frac{v_g^2}{v_c^2} \tag{5}$$

where K_V is the integrity index of the consolidation body (or consolidation coefficient), v_g is the acoustic velocity of the grouting consolidation body and v_c is the acoustic velocity of intact rock. (all acoustic velocity terms are P-wave velocity in this paper.)

Lemaitre [34] proposed in 1984 that the Young's modulus of intact rock and that of rock mass can be expressed by the following equation:

$$E_m = \frac{E}{1 - D} \tag{6}$$

For intact rock, they can be seen as a homogeneous material, and a damaged rock or rock mass can be seen as a heterogeneous material. According to the propagation principle of an elastic wave in a solid matrix, the P wave velocity v_c of intact rock is formed as follows:

$$v_c = \sqrt{\frac{E_r^{'}(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{7}$$

where $E_r^{'}$, μ, and ρ represent the dynamic modulus of elasticity, the Poisson's ratio and the density of the intact rock, respectively. The acoustic velocity $v_c^{'}$ in a heterogeneous material (represents the rock mass or damaged rock here) is expressed as follows:

$$v_c^{'} = \sqrt{\frac{E_m^{'}(1-\mu^{'})}{\rho^{'}(1+\mu^{'})(1-2\mu^{'})}} \tag{8}$$

where $E_m^{'}$, $\mu^{'}$ and $\rho^{'}$ represent the dynamic modulus of elasticity, the Poisson's ratio and the density of rock mass or damaged rock, respectively.

For engineering purposes, the rock mass and intact rocks exhibit the same Poisson's ratio and density. That is,

$$\rho^{'} = \rho \tag{9}$$
$$\mu^{'} = \mu \tag{10}$$

The ratio of the static elastic modulus to the dynamic elastic modulus of intact rock is equal to that of the rock mass (or damaged rock) [35], as follows

$$\frac{E_m}{E_m^{'}} = \frac{E_r}{E_r^{'}} \tag{11}$$

Then, we can obtain the following equation

$$D = 1 - K_V \tag{12}$$

Equation (12) has also been deduced and verified by Wen *et al.* [36] using a large number of point load tests.

Then, the constants m, s and a of the Hoek–Brown failure criterion for grouting the consolidation body can be expressed as:

$$\frac{m}{m_i} = \exp\left(\frac{GSI-100}{14(K_V+1)}\right) \tag{13}$$

$$s = \exp\left(\frac{GSI-100}{3(K_V+6)}\right) \tag{14}$$

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

B. PREDICTION OF THE MECHANICAL PARAMETERS OF THE CONSOLIDATION BODY

The object of this study is to determine the consolidation body after grouting. On the macro scale, the grouting consolidation body is intact and a continuous medium. The slurry and rock block are two different media, so the grouting consolidation body cannot be regarded as a homogeneous medium. In this regard, the grouting consolidation body is considered to be a kind of quasi-rock mass material that is composed of a cementation surface, cement grouting and a rock block. Based on the measured results of the acoustic velocity, the values of m, s and a are computed to estimate the mechanical parameters for the grouting consolidation body.

(2) *GIS* value

Due to the characteristics of the consolidation body, we can only calculate the *RMR* value and the *GSI* value via the empirical equations. At first, Barton proposed the following relationship in 1995 [32]:

$$RMR \approx 15\log Q + 50 \tag{16}$$

Then, Barton put forward the relationship between Q value and v_{p} value in 2002. [33]:

$$Q \approx 10^{v_p - 3.5} \tag{17}$$

Xia *et al.* [37] summarized the results of Barton's research [32], [33], where the *RMR* can be expressed as:

$$RMR \approx 15v_g - 2.5 \tag{18}$$

where the v_{g} is in units of Km/s

Combining this with Hashemi *et al.* [38], the relationships between the *GSI* and the *RMR* is as follows:

$$GSI = RMR_{89} - 5(RMR_{89} > 23) \tag{19}$$

Then,

$$GSI = 15v_g - 7.5 \tag{20}$$

(2) The unconfined compressive strength and tensile strength

The unconfined compressive strength for the grouting consolidation body is obtained by setting $\sigma_3 = 0$ in Eq. (1), giving

$$\sigma_{cm} = \sigma_c s^a \tag{21}$$

and the tensile strength for the grouting consolidation body is

$$\sigma_{tm} = -\frac{s}{m}\sigma_c \tag{22}$$

(3) Young's modulus

In Hoek *et al.* [39], the empirical equations for estimating the Young's modulus is expressed as:

$$E_m = \begin{cases} \left(1-\frac{D}{2}\right)\sqrt{\frac{\sigma_c}{100}}10^{\frac{15v_g-17.5}{40}} & \sigma_c \le 100 \\ \left(1-\frac{D}{2}\right)10^{\frac{15v_g-17.5}{40}} & \sigma_c > 100 \end{cases} \tag{23}$$

According to Eq. (23), the E_m can be rewritten as

$$E_m = \begin{cases} \left(\frac{1}{2}+\frac{K_V}{2}\right)\sqrt{\frac{\sigma_c}{100}}10^{\frac{15v_g-17.5}{40}} & \sigma_c \le 100 \\ \left(\frac{1}{2}+\frac{K_V}{2}\right)10^{\frac{15v_g-17.5}{40}} & \sigma_c > 100 \end{cases} \tag{24}$$

Furthermore, the cohesion and friction angle can be assessed by Hoek *et al.* [39].

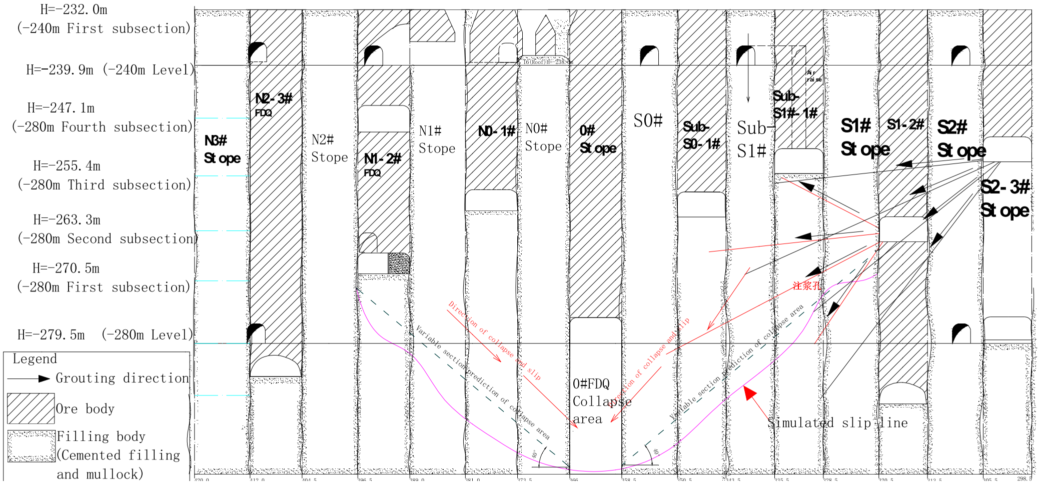


FIGURE 1. The grouting hole layout section.

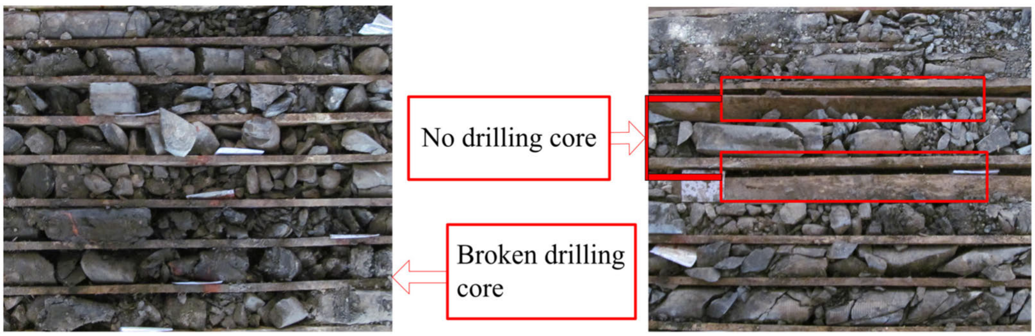


FIGURE 2. Broken drilling core before grouting.

III. GROUTING REINFORCEMENT

A. ENGINEERING BACKGROUND

The Fankou lead-zinc mine was built in 1958 and is one of the largest production bases of lead-zinc mining in china. This mine is located in Shaoguan city in the Guangdong province in southern China. The unsuitable ground pressure treatment in the early mining stages led to the collapse of the mining area, causing it to become a hidden resource. As shown in Figure 1, after the blasting mining of the #0 stope in the Sh-320 m level, due to the untimely filling, the exposed time of the roof was too long, which led to the collapse of the mining area and gave rise to the instability phenomenon of a large area in the adjacent stopes. Based on the existing research results, the blue dotted line refers to the slip line predicted by the drilling holes detection results, and the ocean red solid line is the slip line modeled through the finite element numerical calculation and analysis.

To recycle the resources of the collapsed area, it is necessary to reevaluate the stability and rock mass quality in this area. In this regard, a TRT6000 (True Reflection Tomography 6000) geological exploration was used to measure the fractured structure (crack or cavity) of the rock mass. During testing, the ultrasonic signal cannot be accepted at several target areas. Moreover, there are either no drill cores or extremely broken drill cores in the drilling, which shows that the rock mass is extremely broken in the collapsed area, as shown in Figure 2. Therefore, grouting cement slurry to the collapsed area is proposed, thereby improving the stability and bearing capacity of the fractured rock mass.

B. GROUTING PATTERN

As shown in Figure 1, two grouting steps are performed at the collapsed area in stopes #S2-3 and #S1-2 at elevations of -255.4 m and -263.3 m, respectively. In both steps, the grouting holes are drilled in a fan-shaped manner with differ obliquities. In the first step, there are three groups of fan-shaped holes with distances of 12 m and one group of fan-shaped holes with a distance of 3 m. In the second step, there are four groups of fan-shaped holes with distances of 12 m, 8 m, 10 m and 6 m, respectively. The details of the grouting holes are shown in Figure 1 and Figure 3. In this paper, the main purpose is to study the second step of the grouting reinforcement area. The depth of the grouting holes is listed in Table 1.

We can see from Figure 3 that the collapsed area before grouting is the fractured rock mass, and the broken rock blocks after grouting are consolidated by the cement paste. On the left side of Figure 3 the details of the slurry diffusion

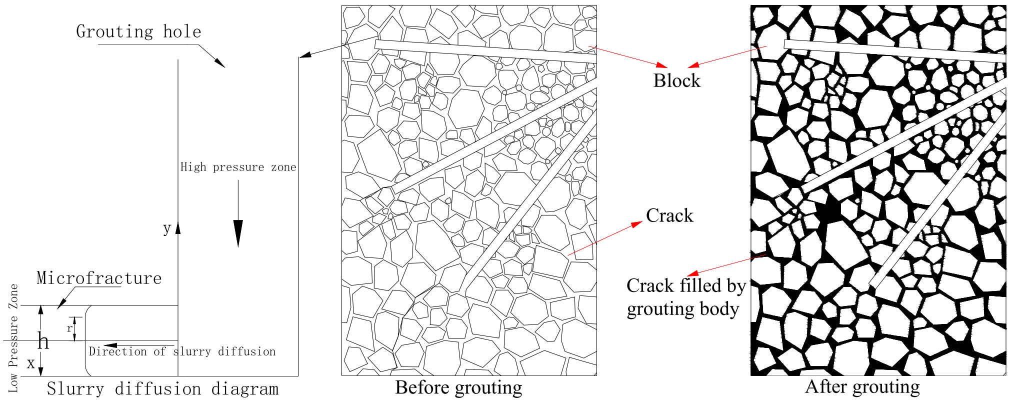


FIGURE 3. Grouting structure and slurry diffusion diagram.

TABLE 1. Grouting quantity statistics.

No.	Depth/m	Grouting volume /m^3	Main filling area of slurry	Remarks
637-YK1	10.5	3.3	S1# Backfilling slag	No
637-ZK1	17.2	13.8	S1# Backfilling slag	No
649-YK1	21.5	15.6	Sub-S1#~S1# Collapse area	Sub-S1#~S1# Collapsing
649-ZK1	14.2	9.0	S1# Backfilling slag	No
657-YK1	16	17.1	S1# Backfilling slag, Sub-S1#~S1#	No
657-ZK1	34.1	22.2	S1#~S0-1#	S0-1# Collapsing
657-ZK2	36	15	S1#~ Sub-S1#	S0-1# Collapsing
657-ZK3	18.1	9.6	S1# Backfilling slag	No
667-YK1	18.3	3.2	S1# Backfilling slag, Sub-S1#~S1# Collapse area	Sub-S1#~S1# Collapsing
667-ZK1	25.9	29.1	S1#~ Sub-S1#	No
667-ZK2	35	99.3	Sub-S1# Non cemented filling	No
667-ZK3	18.2	13.5	S1# Backfilling slag	No
673-YK1	17.7	16.8	S1# Backfilling slag, Sub-S1#~S1#	No
673-ZK1	25.5	31.5	S1#~ Sub-S1#	Sub-S1#
673-ZK2	35	30.5	S1#~S0-1#	Water leakage
673-ZK3	18.6	32.8	S1# Backfilling slag	No

in the grouting holes and cracks in the fractured rock mass are shown. In geomechanics, most people think of consolidation as referring to saturated soils under a sustained load. Therefore, the ''consolidation body'' needs to be redefined here. In this paper, the consolidation body is a macroscopic continuous medium, in which broken rock blocks and a small amount of cemented filling (cementation of slag and tailings) are consolidated by cement paste.

C. GROUTING RESULTS

The main purpose of this grouting is to reinforce the extremely broken rock mass and fill the void formed by the collapse. Ordinary Portland cement, specifically #425 bagged Ordinary Portland cement, is employed as the main grouting material. The different water-cement ratios are designed to be 1.2, 1 and 0.8. First, the water-cement ratio is 1.2 and gradually thickens. Finally, the water-cement ratio is mainly filled with a 1:1 pure cement slurry. The grouting method in the article is the grouting of the orifice pressure. The subsection grouting and the final grouting pressure are 0.3-0.5 MPa and 0.5-0.8 MPa, respectively. To effectively cover the sliding surface of the collapsed area, the designed grouting holes are shown in Figure 1 and Figure 4. In Figure 4, the solid red line and thick black lines are different stages of the grouting hole. The statistical results of the quantity of grouting engineering are shown in Table 1.

D. GROUTING EFFECT DETECTION

1) DRILLING CORE COMPARISON

As shown in Figure 2, the drilling core is broken in the vicinity of the slip zone and the drilling core is not even

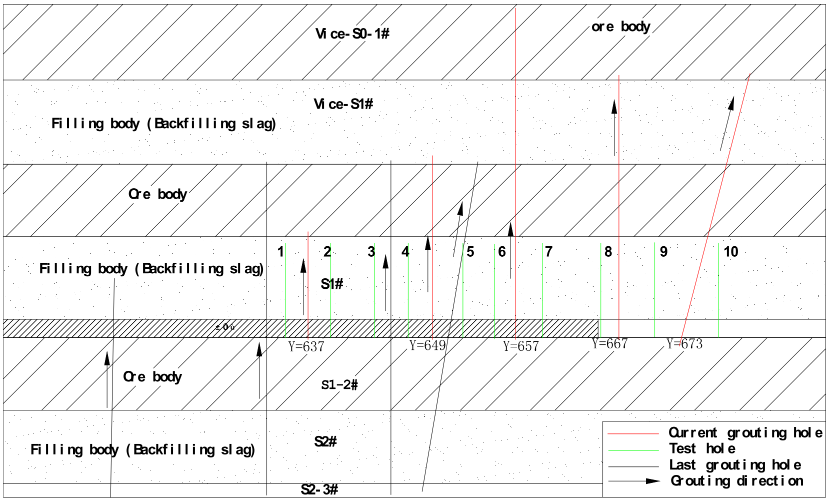


FIGURE 4. The grouting hole and test hole layout plan.

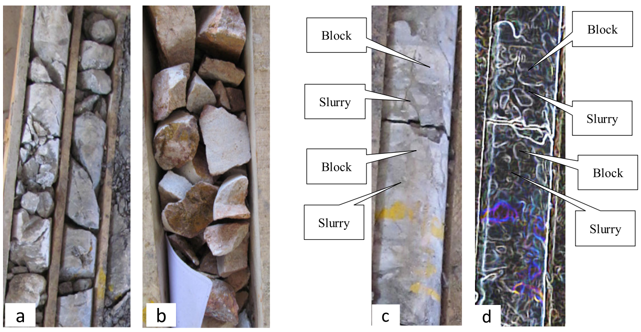


FIGURE 5. Core control chart before and after grouting.

in several positions before the grouting. The drilling core contrast before and after grouting is shown in Figure 5. It can be clearly seen that the slurry is consolidated in the broken rock after grouting.

2) THE PACKER PERMEABILITY TEST AND RQD VALUE

To test the consolidation effect of the slurry, the packer permeability test, which is sustained for 30 minutes with the maximum pressure kept consistent with the grouting pressure, is performed in each borehole before and after grouting. When the opening of the mouth appears to obviously contain water, that is, at the end of the packer permeability test, the final flow value is counted to calculate the water permeability. The water permeability formula q_t is as follows:

$$q_t = \frac{Q_0}{L_0 P_0} \tag{25}$$

where Q_0 is the flow rate, L/min, L_0 is the length of the pressure water section, m, and P_0 is the pressure, MPa. As shown in Table 6, the permeability rate of the grouting hole fluctuated from 58.7 Lugeon (Lu) to 116.7 Lu before grouting, and the retested water permeability is less than 10 Lu after grouting.

Rock Quality Designation (RQD), which is a common international method to identify the quality of rock engineering, was proposed and developed by the University of Illinois in the United States. In this paper, RQD statistics are performed to compare the consolidation effect of grouting in 6 boreholes before and after grouting. The results of the RQD statistics and water permeation rate are listed in Table 6. RQD fluctuates between 39.7% and 54.2% before grouting and between 68.7% and 74.5% after grouting. The shows that the grouting make the RQD value obviously rise.

3) ACOUSTIC TESTING

We tried to perform the rock mass acoustic test in the collapsed area before grouting. The clean water was injected into the test hole as the coupling medium in the Acoustic test. Because the rock mass is too broken in the collapsed area, the Acoustic testing hole cannot be filled with water, leading to the test hole being unable to obtain the Acoustic velocity of the rock mass. There are 10 Acoustic testing holes in the grouting tunnel. Generally, the final setting time of the 42.5# ordinary Portland cement is 28 days. Therefore, the Acoustic testing of the rock mass is conducted once again for the grouting area after 30 days of grouting.

The Acoustic test is based on the RSM-SY5 (T) intelligent acoustic tester, which collects acoustic test data through a single-hole device transducer. The theory of measurement is shown in Figure 6, and the Acoustic velocity is calculated as follows:

$$V_p = \frac{\Delta L}{t_2 - t_1} \tag{26}$$

where V_p is the Acoustic velocity in the rock mass, t_2 is the time of propagation of the energy from the transmitter R to R_2, and t_1 is the time for the propagation of energy from the transmitter R to R_1.

An attempt is made to determine the acoustic velocity of the rock mass before grouting. Because the rock mass is

TABLE 2. Slurry consolidation effect monitoring table.

No.	Depth/m	RQD value			Permeable rate/Lu		
		Before grouting	After grouting		Before grouting	After grouting	Reduction multiplier
637-YK1	10.5	45.2%	Borehole 1	72.1%	85.6	3.1	26.61
637-ZK1	17.2	39.7%	Borehole 2	69.8%	58.7	4.6	11.76
649-YK1	21.5	51.8%	Borehole 3	74.5%	92.7	7.3	11.70
649-ZK1	14.2	46.3%	Borehole 4	72.4%	69.3	4.5	14.40
657-YK1	16	53.1%	Borehole 5	68.7%	90.1	9.2	8.79
657-ZK1	34.1	42.6%	Borehole 6	71.9%	103.8	9.5	9.93
657-ZK2	36	49.1%	Borehole 7	70.2%	113.4	6.8	15.68
657-ZK3	18.1	41.8%	Borehole 8	67.8%	86.5	7.4	10.69
667-YK1	18.3	52.9%	Borehole 9	72.7%	77.4	8.1	8.56
667-ZK1	25.9	47.5%	Borehole 10	69.3%	98.5	5.6	16.59
667-ZK2	35	43.8%	--	--	106.4	9.7	9.97
667-ZK3	18.2	50.6%	--	--	93	6.4	13.53
673-YK1	17.7	47.2%	--	--	69.8	6.8	9.26
673-ZK1	25.5	40.8%	--	--	105.2	7.9	12.32
673-ZK2	35	54.2%	--	--	116.7	9.7	11.03
673-ZK3	18.6	48.4%	--	--	84.3	6.3	12.38

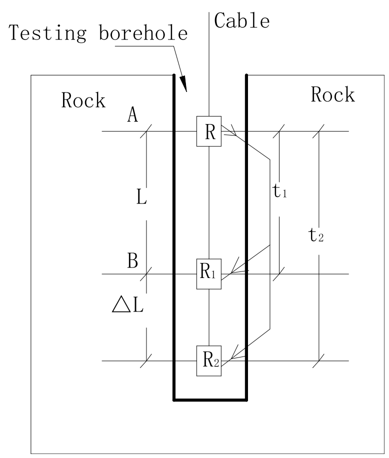


FIGURE 6. Acoustic test schematic.

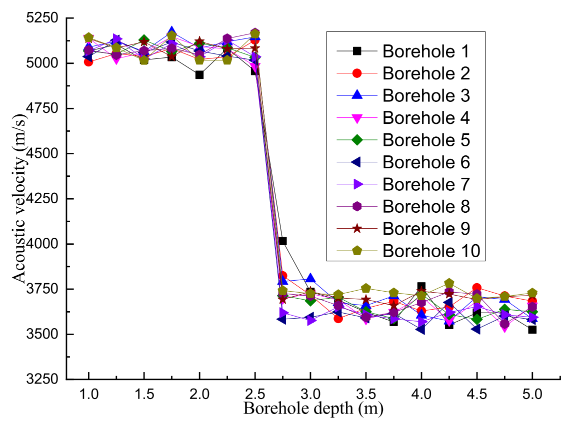


FIGURE 7. Acoustic test results after grouting.

extremely broken or in an empty area, testing the Acoustic velocity for the grouting hole fails. The grouting is completed after 30 days, and the Acoustic velocity test is once again conducted in the grouting area. To ensure the accuracy of the test and ensure that the grouting area is not interfered by engineering and blasting vibration, there is no construction disturbance or blasting operation near the grouting area. The Acoustic velocity of the test depth between 1 m and 2.5 m is obviously greater than the Acoustic velocity between 2.5 m and 5 m, as shown in Figure 7, mainly due to a 2.5 m thick safety pillar of 2.5 m thick retained between the stope and pillar.

IV. EVALUATION OF THE MECHANICAL PARAMETERS OF THE CONSOLIDATION BODY

A. ROCK MECHANICS LABORATORY TEST

To evaluate the mechanical parameters of the consolidation body, and the physical and mechanical properties of the intact rock, the ore body and filling body in this area are tested in a laboratory. The mechanical parameter of grouting consolidation body is also determined to compare it with the evaluation value. We adopt conventional mechanical testing methods. The physical and mechanical parameters are tested using ISRM [40] suggested testing methods. The tested results are listed in Table 3.

TABLE 3. The measured values of rock mechanics parameters.

Name	ρ (t/m^3)	UCS(MPa)		Acoustic(m/s)		BTS(MPa)		E(GPa)	c(MPa)	Φ(°)	μ
		Dry	Saturation	Dry	Saturation	Dry	Saturation				
Ore	3.46	142.48	123.25	5606.3	6075.1	7.6	6.4	54.46	29.9	42.71	0.25
Rock	2.71	113.52	90.88	4136.7	5537.7	4.8	4.1	23.35	16.62	44.89	0.28
Filling	1.72	4.85	--	2530.8	--	0.92	1.06	2.15	1.81	41.58	0.21
Consolidation body	2.67	5.36	3.67	3428.3	3861.7	0.57	0.34	10.27	1.28	34.1	--

where ρ is density, E is modulus of elasticity, Φ is Friction angle, c is Cohesion, and μ is Poisson ratio.
Noted: Filling is the cementation of slag and tailings.

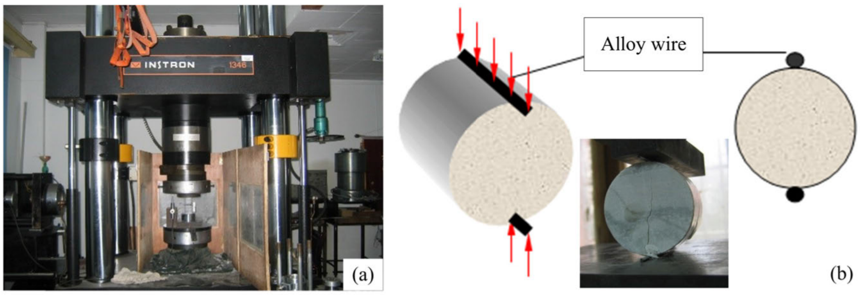


FIGURE 8. The mechanics test of intact rock samples(a, Uniaxial compressive strength test; b, Brazilian splitting test).

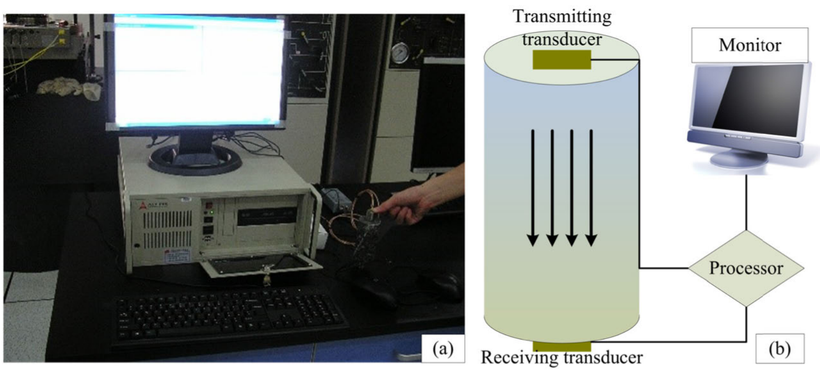


FIGURE 9. The acoustic velocity test of intact rock samples (a, Testing process; b, Sketch map).

The sample tested in this paper is prepared according to the ISRM [41] suggested standard sample. The size of uniaxial compressive strength specimens are 100 mm × 50 mm, and uniaxial tensile strength specimens are 50 mm × 50 mm. The uniaxial compressive strength was measured using a hydraulic servo mechanical testing machine (INSTRON-1346, INSTRON, Melbourne, Australia) following ASTM [2] standards, as shown in Fig. 8(a). The uniaxial tensile strength is obtained by Brazilian splitting test, as shown in Fig. 8(b).

According to the ISRM [40] suggested testing methods, an acoustic emission testing system (ADLINK, USA) was used to measure the acoustic velocity. The testing process is shown vividly in Figure 9.

The elastic modulus and Poisson's ratio were determined using the uniaxial compression deformation test, as follows

$$E = \frac{\sigma_b - \sigma_a}{\varepsilon_{hb} - \varepsilon_{ha}} \tag{27}$$

$$\mu = \frac{\varepsilon_{db} - \varepsilon_{da}}{\varepsilon_{hb} - \varepsilon_{ha}} \tag{28}$$

where E is the elastic modulus of intact rock, μ is the Poisson's ratio of intact rock, σ_a is the stress value at the starting point of linear section on the relation curve between stress and longitudinal strain, σ_b is the stress value at the end of the linear section on the relation curve between stress and longitudinal strain, ε_{ha} is the longitudinal strain corresponding to stress σ_a, ε_{hb} is the longitudinal strain corresponding to stress

TABLE 4. Hoek-brown constants.

Name	lithology	Weathering degree	m_i	m	s	a
Parameter	Limestone or dolomite	weak weathering	7	0.5639	0.000882	0.5068

TABLE 5. Mechanical parameters of the grouting consolidation body predicted by ultrasonic velocity.

Name	σ_c (Saturation)	GSI	σ_{cm}(MPa)	σ_{tm}(MPa)	E_m(GPa)	c_m (MPa)	Φ_m(°)
Consolidation body	123.25(Ore)	47.46	3.489	0.214	7.875	1.47	34.2
Consolidation body	90.88(Rock mass)		2.573	0.158	6.136	1.13	30.8

TABLE 6. Comparison table between evaluation value and measured value.

	Nmae	ρ (t/m^3)	σ_{cm} (MPa)	σ_{tm} (MPa)	E_m (GPa)	c_m (MPa)	Φ_m(°)
Testing	Consolidation body	2.67	2.72	0.161	6.214	1.18	32.8
Predicted value	Consolidation ore body	--	3.489	0.214	7.875	1.47	34.2
	Consolidation rock body	--	2.573	0.158	6.136	1.13	30.8
Deviation	Consolidation ore body	--	-27.94%	-32.92%	-26.73%	-24.58%	-4.27%
	Consolidation rock body	--	5.51%	1.86%	1.26%	4.24%	6.098%

σ_b, ε_{da} is is the transverse strain corresponding to stress σ_a, ε_{db} is is the transverse strain corresponding to stress σ_b. The physical and mechanical parameters of the reinforced rock mass are obtained by the same method mentioned above.

B. EVALUATION OF THE MECHANICAL PARAMETERS OF THE CONSOLIDATION BODY

The Acoustic velocity of the consolidated body is shown in Figure 7 with an average of 3664.3 m/s (3.664 Km/s). The GSI value is obtained by the empirical formula (20) and the calculation results of the Hoek-Brown parameters of the grouting consolidation body are shown in Table 4. The mechanical parameters of the grouting consolidation body are listed in Table 5.

In Table 4, m_i is the m value of the intact rock, and the Hoek-Brown constant of the consolidation body is calculated by formulas (5) and (13) to (15). When the mechanical parameters of the consolidation body are calculated, the consolidation body is regarded as a quasi-rock mass material. Since the main components of the fractured rock mass before grouting are the ore body or rock mass, the uniaxial compressive strength of the intact ore body and rock are taken as the calculation parameters, respectively, and the mechanical parameters of the consolidation body are calculated using formulas (21) to (24).

In this paper, a comparative analysis is conducted between the predicted and measured results. As shown in Table 6, the predicted mechanical parameters, which are evaluated using the rock strength, are strongly matched with the measured values, with the deviation fluctuating between 1.26% and 6.098%. However, the predicted mechanical parameters using ore strength show a strongly negative deviation that fluctuates between 8.62% and 31.6%. This result is consistent with the

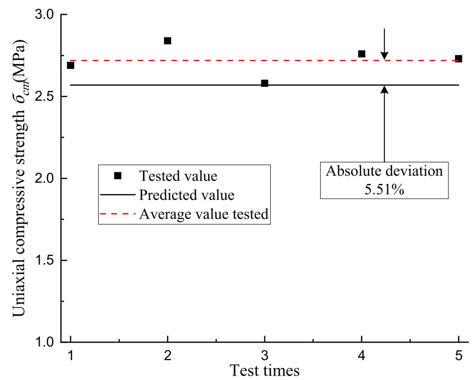


FIGURE 10. AD of uniaxial compressive strength.

actual situation in the field. The rock block is the main filling material in the grouting area of the collapsed area. Thus, the deviation calculated using the rock strength between the tested value and the predicted value is less than that of the ore strength. These research results show that the Hoek-Brown criterion based on the Acoustic can precisely predict the mechanical properties of the grouting consolidation body. It is reasonable that the Acoustic is used to predict the mechanical properties of the grouting consolidation body based on the parameter of the aggregate in the grouting consolidation body.

From Figure 10 to Figure 14 provide some interesting data regarding tested value and predicted value. It is clear from the figures that the predicted value is less than the average value of the measured value, this reflects the great differences that exist between cement paste and rock block. It can be seen from the figures that the slight absolute deviation (AD) that exist between predicted value and the average value of the

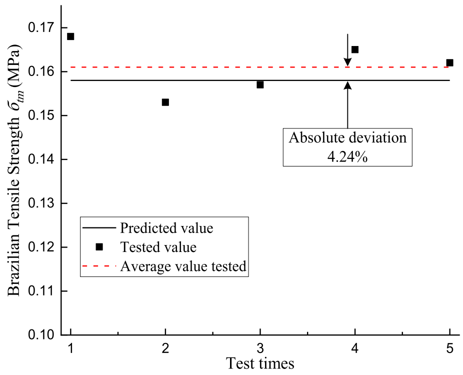


FIGURE 11. AD of brazilian tensile strength.

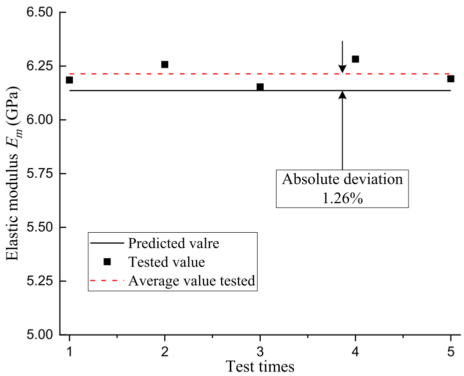


FIGURE 12. AD of elastic modulus.

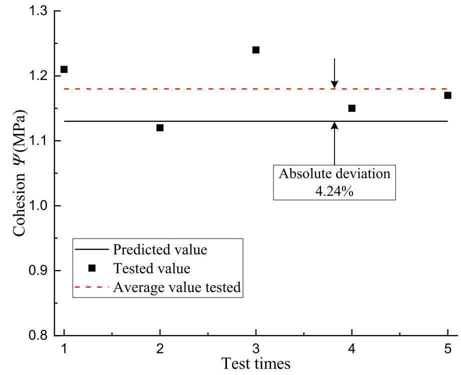


FIGURE 13. AD of cohesion.

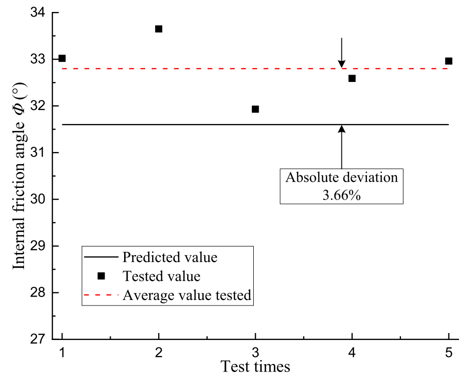


FIGURE 14. AD of internal friction angle.

measured value. This suggests that the predicted values are reliable when the materials are consistent.

V. DISCUSSION

The Acoustic velocity is a key parameter in mining engineering, geotechnical engineering and construction engineering and has a broad development prospect when evaluating the mechanical properties (parameters) of grouting consolidation in the collapsed area of underground mines via Acoustic velocity. In-situ Acoustic velocity measurements are more convenient than sampling for laboratory testing. When the Acoustic velocity is used to evaluate the parameters of the consolidation body, a key problem should be paid attention to, that is, the composition of the consolidation body. In this paper, the main components of the consolidation body include the broken rock blocks, the cement paste (grouting material) and a small amount of the cemented filling body (cementation of slag and tailings). Therefore, it is particularly important to obtain the mechanical parameters of the rock blocks. As shown in Table 6, different aggregates have different evaluation results. In this study, because the content of the filling body is lower, only the rock mass is considered as the calculation target. In addition, the consolidation range of the grouting also needs to be clarified to ensure that it is completely consolidated within the assessment range.

The acoustic velocity and density of ore-rock mass are much higher than those of rock mass. Therefore, in order to ensure that the consolidation body is a mixture of rock mass and cement paste, the acoustic velocity and density of reinforced rock mass should be less than or equal to those of ore-rock. Then, the sample tested can be determined as a consolidation of cement paste and rock block. If the acoustic velocity and density of the consolidated body are greater than those of the intact rock mass, the ore-rock mass may be contained in the consolidated body and the sample would be excluded. Acoustic velocity is a key parameter in this paper, and the measurement of acoustic velocity depends on the operation process of the tester. In addition, some equations derived in this paper are obtained from empirical relations. This leads to certain uncertainties in the empirical relationship. Therefore, when using empirical relationships, we have to reduce test errors through multiple tests. In each sample test, there are at least five test results with an error of less than 5%. Finally, the average value of data tested is used to calculate the other mechanic parameters which obtain from empirical relationships derived in this paper.

VI. CONCLUSION

The results of this study show that the method proposed in this paper can effectively and accurately evaluate the mechanical parameters of the grouting consolidation body and can effectively reduce the workload, time consumption and the cost of laboratory tests. Therefore, the method proposed in this paper can not only give full play to the convenience of the Acoustic velocity of the rock mass but also provides a simple and practical method for evaluating the strength of the consolidation body. It should be emphasized that when using this method to evaluate the mechanical parameters of the grouting consolidation body, the components and materials of the block in the grouting consolidation body must be mastered in detail. Table 6 shows that different block types of the grouting consolidation body will lead to varied evaluation results.

In conclusion, this method of the Acoustic velocity test combined with the modified Hoek-Brown criterion can evaluate the mechanical parameters of the consolidation body. The current method has been shown to have high feasibility and reliability, and the evaluated value is close to the measured value in the laboratory. Therefore, the method proposed in this paper has broad application prospects.

REFERENCES

[1] *Test Methods For Ultra Violet Velocities Determination*, document 2845, ASTM, American Society for Testing and Materials, West Conshohocken, PA, USA, 1983.

[2] *Standard Test Method of Unconfined Compressive Strength of Intact Rock Core*, document 2938, ASTM, West Conshohocken, PA, USA, 1986.

[3] *Engineering and Design-Rock Foundations*, document EM 1110-1-2908, United States Corps of Engineers (USACE), Washington, DC, USA, 1994.

[4] *Technical Engineering and Design Guides as Adapted From the US Army Corps of Engineers*, New York, NY, USA: ASCE, 1996.

[5] *Standard Specifications for Highway Bridges. American Association of State Highway and Transportation Officials*, Washington, DC, USA, AASHTO, 1997.

[6] "Canadian foundation engineering manual," in *Canadian Geotechnical Society*, 4th ed. Vancouver, Canada: Bitech Publishers Ltd, 2006.

[7] M. Singh, A. Raj, and B. Singh, "Modified Mohr—Coulomb criterion for non-linear triaxial and polyaxial strength of intact rocks," *Int. J. Rock Mech. Mining Sci.*, vol. 48, no. 4, pp. 546–555, 2011.

[8] M. Singh and B. Singh, "Modified Mohr-Coulomb criterion for non-linear triaxial and polyaxial strength of jointed rocks," *Int. J. Rock Mech. Mining Sci.*, vol. 51, pp. 43–52, Apr. 2012. doi: 10.1016/j.ijrmms.2011.02.004.

[9] A. J. Li, R. S. Merifield, and A. V. Lyamin, "Effect of rock mass disturbance on the stability of rock slopes using the Hoek–Brown failure criterion," *Comput. Geotechnics*, vol. 38, no. 4, pp. 546–558, 2011. doi: 10.1016/j.compgeo.2011.03.003.

[10] J. C. Jaeger, "Friction of rocks and stability of rock slopes," *Geotechnique*, vol. 21, no. 2, pp. 97–134, 1971.

[11] E. Hoek and J. W. Bray, *Rock Slope Engineering*, 3rd ed. London, U.K.: Institute of Mining and Metallurgy, 1981.

[12] R. E. Goodman, *Introduction to Rock Mechanics*, 2nd ed. 1989, New York, NY, USA: Wiley.

[13] A. J. Li, R. S. Merifield, and A. V. Lyamin, "Stability charts for rock slopes based on the Hoek-Brown failure criterion," *Int. J. Rock Mech. Mining Sci.*, vol. 45, no. 5, pp. 689–700, 2008. doi: 10.1016/j.ijrmms.2007.08.010.

[14] H. Mori and T. Tanaka, "Seismic stability analysis of slope by finite element method employing a strain-softening elasto-plastic model," *Trans. Jpn. Soc. Irrigation Drainage Rural Eng.*, vol. 76, no. 254, pp. 205–209, 2008.

[15] C. H. Wei, W. C. Zhu, Q. L. Yu, T. Xu, and S. Jeon, "Numerical simulation of excavation damaged zone under coupled thermal-mechanical conditions with varying mechanical parameters," *Int. J. Rock Mech. Mining Sci.*, vol. 75, pp. 169–181, Apr. 2015. doi: 10.1016/j.ijrmms.2014.11.010.

[16] E. Karampinos, J. Hadjigeorgiou, J. Hazzard, and P. Turcotte, "Discrete element modelling of the buckling phenomenon in deep hard rock mines," *Int. J. Rock Mech. Mining Sci.*, vol. 80, pp. 346–356, Dec. 2015. doi: 10.1016/j.ijrmms.2015.10.007.

[17] Z. Yang, S. Zhai, Q. Gao, and M. Li, "Stability analysis of large-scale stope using stage subsequent filling mining method in Sijiaying iron mine," *J. Rock Mech. Geotech. Eng.*, vol. 7, no. 1, pp. 87–94, 2015. doi: 10.1016/j.jrmge.2014.11.003.

[18] E. Hoek and E. T. Brown, "Empirical strength criterion for rock masses," *J. Geotech. Eng. Division*, vol. 106, no. 15715, pp. 1013–1035, 1980. doi: 10.1016/0148-9062(81)90766-X

[19] E. Hoek, C. Carranza-Torres, and B. Corkum, "Hoek-Brown failure criterion-2002 edition," in *Proc. North Amer. Rock Mech. Soc. Meeting Toronto*, 2002, pp. 267–273.

[20] X. L. Yang, "Seismic displacement of rock slopes with nonlinear Hoek-Brown failure criterion," *Int. J. Rock Mech. Mining Sci.*, vol. 44, no. 6, pp. 948–953, 2007. doi: 10.1016/j.ijrmms.2007.01.002.

[21] T. Jing and Y. Liu, "Bearing capacity calculation of rock foundation based on nonlinear failure criterion," *Ieri Proc.*, vol. 1, no. 11, pp. 110–116, 2012. doi: 10.1016/j.ieri.2012.06.018.

[22] Z. Saada, S. Maghous, and D. Garnier, "Bearing capacity of shallow foundations on rocks obeying a modified Hoek-Brown failure criterion," *Comput. Geotechnics*, vol. 35, no. 2, pp. 144–154, 2008. doi: 10.1016/j.compgeo.2007.06.003.

[23] R. S. Merifield, A. V. Lyamin, and S. W. Sloan, "Limit analysis solutions for the bearing capacity of rock masses using the generalised Hoek-Brown criterion," *Int. J. Rock Mech. Mining Sci.*, vol. 43, no. 6, pp. 920–937, 2006. doi: 10.1016/j.ijrmms.2006.02.001.

[24] A. Keshavarz, A. Fazeli, and S. Sadeghi, "Seismic bearing capacity of strip footings on rock masses using the Hoek-Brown failure criterion," *J. Rock Mech. Geotech. Eng.*, vol. 8, no. 2, pp. 170–177, 2016. doi: 10.1016/j.jrmge.2015.10.003.

[25] K. Kikuchi, T. Igari, Y. Mito, and S. Utsuki, "*In situ* experimental studies on improvement of rock masses by grouting treatment," *Int. J. Rock Mech. Mining Sci.*, vol. 34, nos. 3–4, p. 138, 1997. doi: 10.1016/S1365-1609(97)00183-4.

[26] W. Li and Q. Wu, "Grout improvement effect in jointed rock slope by numerical modeling method," *Electron. J. Geotech. Eng.*, vol. 18, pp. 259–268, 2013. doi: 10.1145/2502524.2502578.

[27] S. Utsuki, "*In-situ* experimental studies on improvement of deformability of rock masses by grout treatment," *Jpn. Committee Rock Mech.*, vol. 9, no. 1, pp. 7–8, 2013.

[28] A. Zolfaghari, A. S. Bidar, M. R. M. Javan, M. Haftani, and A. Mehinrad, "Evaluation of rock mass improvement due to cement grouting by Q-system at Bakhtiary dam site," *Int. J. Rock Mech. Mining Sci.*, vol. 74, pp. 38–44, Feb. 2015. doi: 10.1016/j.ijrmms.2014.12.004

[29] E. Hoek and E T. Brown, *Underground Excavation in Rock*, London, U.K.:, Institute Mining Metallurgy, 1980.

[30] E. A. Hoek. (2004). *Brief History of the Development of the Hoek-Brown Failure Criterion*. [Online]. Available: http: //www. rocscience

[31] Z. T. Bieniaski, "Rock mass classification in rock engineering," in *Proc. Explor. For Rock Eng. Rock Mech. Symp.*, Balkema, Cape Town, 1976.

[32] N. Barton, *Geotechnical Design World Tunnelling*. 1991, pp. 6–410.

[33] N. Barton, "Some new Q-value correlations to assist in site characterisation and tunnel design," *Int. J. Rock Mech. Mining Sci.*, vol. 39, no. 2, pp. 185–216, 2002. doi: 10.1016/S1365-1609(02)00011-4.

[34] J. Lemaitre, "How to use damage mechanics," *Nucl. Eng. Des.*, vol. 80, pp. 233–245, Jul. 1984. doi: 10.1016/0029-5493(84)90169-9.

[35] A. Palmström and R. Singh, "The deformation modulus of rock masses—Comparisons between *in situ* tests and indirect estimates," *Tunnelling Underground Space Technol.*, vol. 16, no. 3, pp. 115–131, 2001. doi: 10.1016/S0886-7798(01)00038-4.

[36] L. Wen, Z. Q. Luo, and S.-J. Yang, "Analyses and calculation of point load strength on rock mass damage index," (in Chinese), *Chin. J. Eng.*, vol. 2, pp. 175–181, 2017. doi: 10.13374/j.issn2095-9389.2017.02.002.

[37] K. Z. Xia, C. Cong-Xin, and L. Xiu-Min, "Estimation of rock mass mechanical parameters based on ultrasonic velocity of rock mass and Hoek-Brown criterion and its application to engineering," (in Chinese), *Chin. J. Rock Mech. Eng.*, vol. 32, no. 7, pp. 1458–1466, 2013. doi: 10.3969/j.issn.1000-6915.2013.07.022.

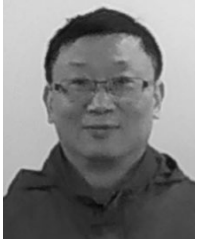
[38] M. Hashemi, S. Moghaddas, and R. Ajalloeian, "Application of rock mass characterization for determining the mechanical properties of rock mass: A comparative study," *Rock Mech. Rock Eng.*, vol. 43, no. 3, pp. 305–320, 2010. doi: 10.1007/s00603-009-0048-y.

[39] E. Hoek, P. K. Kaiser, and A. A. Balkema, W. F. Bawden, *Support of Underground Excavations in Hard Rock*. Rotterdam, The Netherlands, 1995.

[40] J. A. Franklin, "Suggested method for determining point load strength," *Int. J. Rock Mech. Mining Sci. Geomech. Abstr.*, vol. 22, pp. 51–60, Apr. 1985.

[41] "The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring, 1974-2006," in *Suggested Methods Prepared by the Commission on Testing Methods*(International Society for Rock Mechanics), R. Ulusay and J. A. Hudson, Eds., Salzburg: ISRM, 2007, p. 293.

LEI WEN received the B.S. degree from the College of Safety Engineering, North China Institute of Science and Technology, China, in 2011, and the M.S. degree from the University of South China, China, in 2014. He is currently pursuing the Ph.D. degree with Central South University, China. His research interest includes rock damage in mining engineering and its applications.



ZHOU QUAN LUO received the B.S., M.S., and Ph.D. degrees from the Department of Resources Development Engineering, Central South University of Technology, China, in 1987, 1990, and 1999, respectively. He is currently a Professor and the Dean of the School of Resources and Safety Engineering, Central South University. His research interests include mining engineering and rock mechanics.

YA GUANG QIN received the B.S. degree in safety academy from Henan Polytechnic University, China, in 2013, and the M.S. degree from the University of South China, China, in 2016. He is currently pursuing the Ph.D. degree with Central South University, China. His research interests include safety engineering and rock mechanics.

ZHEN YAN LUO received the B.S. degree from the School of Resources and Safety Engineering, Central South University, China, in 2011, and the M.S. degree from the Central South University, in 2014, where he is currently pursuing the Ph.D. degree.

• • •