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Experimental investigation on quantitative evaluation of rock hardness based on impact energy dissipation index

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Abstract

Rock hardness is an important indicator reflecting the relative hardness, drillability, and blastability of rock formation. Accurate interpretation of the response of percussion drilling tools can provide new possibilities for in-situ, rapid, and quantitative evaluation of rock hardness. High-precision digital displacement, hydraulic pressure, and rotational speed sensors were used to monitor the key transmission parts of the percussion drill, and a digital monitoring system for the drilling process was then established. Rock hardness measurement and orthogonal tests of percussion drilling were parallelly carried out, and a standard database containing response data of the drill when drilling various types of rocks was established. Functional relationships between propelling pressure, percussion pressure, rotational speed, and impact energy dissipation were developed, and a novel method to quantitatively evaluate rock hardness based on impact energy dissipation index was proposed. The performed tests and analyses revealed that there is an inverse linear relationship between the propelling pressure and impact energy dissipation. The fitting curve of percussion pressure and drilling energy dissipation is an open upward parabola, and the curves for various rocks have the same symmetry axis but different curvature radii. The influence of rotational speed of drill rod on drilling energy dissipation is negligible. By dimensionless treatment of drilling energy dissipation per unit volume, the influence of mechanical parameters of percussion drilling is removed, and the impact energy dissipation index �, which has low discreteness and a good correlation with rock hardness, was defined to characterize the rock hardness. The response data of the drilling process in conventional boreholes were obtained and interpreted by the digital sensing technology, and the obtained data were used to determine the rock hardness without additional survey or test, which puts forward a new way for direct evaluation of rock mass parameters on engineering sites.

Keywords

rock hardness, percussion drill, impact energy dissipation index, propelling pressure, percussion pressure, rotational speed of drill rod

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Experimental investigation on quantitative evaluation of rock hardness based on impact energy dissipation index

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Abstract: Rock hardness is an important indicator reflecting the relative hardness, drillability, and blastability of rock formation. Accurate interpretation of the response of percussion drilling tools can provide new possibilities for in-situ, rapid, and quantitative evaluation of rock hardness. High-precision digital displacement, hydraulic pressure, and rotational speed sensors were used to monitor the key transmission parts of the percussion drill, and a digital monitoring system for the drilling process was then established. Rock hardness measurement and orthogonal tests of percussion drilling were parallelly carried out, and a standard database containing response data of the drill when drilling various types of rocks was established. Functional relationships between propelling pressure, percussion pressure, rotational speed, and impact energy dissipation were developed, and a novel method to quantitatively evaluate rock hardness based on impact energy dissipation index was proposed. The performed tests and analyses revealed that there is an inverse linear relationship between the propelling pressure and impact energy dissipation. The fitting curve of percussion pressure and drilling energy dissipation is an open upward parabola, and the curves for various rocks have the same symmetry axis but different curvature radii. The influence of rotational speed of drill rod on drilling energy dissipation is negligible. By dimensionless treatment of drilling energy dissipation per unit volume, the influence of mechanical parameters of percussion drilling is removed, and the impact energy dissipation index η, which has low discreteness and a good correlation with rock hardness, was defined to characterize the rock hardness. The response data of the drilling process in conventional boreholes were obtained and interpreted by the digital sensing technology, and the obtained data were used to determine the rock hardness without additional survey or test, which puts forward a new way for direct evaluation of rock mass parameters on engineering sites.

Keywords: rock hardness; percussion drill; impact energy dissipation index; propelling pressure; percussion pressure; rotational speed of drill rod

1 Introduction

Rock hardness, an important indicator reflecting the relative hardness, drillability, and blastability of rock formation, has become an increasingly important hot topic in tunnel blasting, full-face tunnelling by tunnel boring machine (TBM), and mine blasting[1]. The ignorance of rock hardness in engineering construction may bring about some negative impacts[2]. For example, TBM cutters are subject to high stress when breaking rocks, and abnormal wear of cutters and sudden drop of tunneling efficiency may be caused if the toughness and hardness of cutter match improperly with rock hardness. The maintenance duration of TBM cutters when tunnelling the hard rock section in Hanjiang-to-Weihe River Water Transfers Project accounts for more than 30% of the construction time, and the related expenses incurred only by cutters account for about 1/3 of the tunneling cost[3]. Therefore, Bruland[4], Yan et al.[5], and Liu et al.[6] all suggest that rock hardness be regarded as an important indicator in surrounding rock classification method when TBM is adopted.

Rock hardness is usually determined by hardness tester[7], weighted summation of mineral hardness[8], and conversion using compressive strength[9]. However, sampling, processing, and testing are often time-consuming and labor-intensive in above approaches, and it is difficult to feedback test data without delay. Therefore, it is urgent to develop a method to direct evaluate rock hardness on engineering sites. Drilling is an indispensable construction operation, and the drilled holes can be found as blastholes in tunnel or mining blasting, grouting holes in rock masses, and advanced exploration holes for TBM construction. During drilling, drilling tools are in direct contact with rock masses, and the response information of drilling tools can comprehensively convey the mechanical properties of rock masses[10]. As a result, it is of significant research and application value to obtain rock hardness quantitatively and in real time during drilling.

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The digital drilling technology[11] embracing high-precision digital sensors and data acquisition instruments can automatically and continuously collect massive drilling tool response information during rock drilling, such as displacement, time, pressure, and rotational speed of drill rod, and engineering parameters of rock masses saved in those data are then fully interpreted according to the principles of mechanical balance[12] or energy conservation[13]. In recent years, the research in the digital drilling technology has made considerable headway. The soft–hard uneven composite strata was identified using pure rate of penetration[14], the evaluation level of rock mass quality was improved through monitoring drilling process[15], the relationship between digital information while drilling and uniaxial compressive strength of rocks was established[16], and the surrounding rock mass classification method was proposed based on drilling energy theory[13]. When establishing the relationship between response parameters while drilling and mechanical parameters of rocks, it is usually assumed that the drilling speed or drilling energy dissipation for the same rock is constant[15–17]. However, through laboratory and field tests, Cao et al.[11] revealed that the rotary drilling speed is related to not only rock properties, but also drilling parameters such as propelling pressure and rotational speed of drill rod, and the impact energy dissipation is also affected by drilling parameters. Therefore, we should explore novel drilling response parameters that should be unique for the same rock, so as to characterize mechanical parameters of rocks more accurately.

Percussion drilling tests and rock hardness measurement were parallelly carried out, and a standard database containing drilling response information when drilling various types of rocks was established. The relationships between propelling pressure, percussion pressure, rotational speed, and impact energy dissipation were deeply investigated, and the impact energy dissipation index was then defined to quantitatively characterize rock hardness. The reliability and applicability of the new method were verified by laboratory tests and engineering applications, and the results can provide a new idea for rapid determination of rock hardness on engineering sites.

2 Percussion drilling tests

2.1 Test equipment and data acquisition

Digital sensors were installed at the critical transmission parts of percussion drill to measure important response information during percussion process in real time, and automatic data acquisition instruments were connected to realize digital monitoring of percussion drilling (Fig. 1(a)). Based on the digital sensors and data acquisition instruments, percussion drilling tests for rocks were performed (Fig.1 (b)).

During digital monitoring of percussion drilling, the distance S between the drill rod and the bit was measured using a draw-wire displacement sensor, the propelling pressure P_r and the percussion pressure P_e were monitored by a high-precision hydraulic sensor, and the rotational speed of drill rod N was identified with a switch Hall sensor. All those parameters were collected synchronously according to the drilling time T at a frequency of 5 Hz. The automatic data acquisition instrument was equipped with a large-capacity storage, and the standard data of positioning and drilling processes for single borehole were stored as separate files.

2.2 Test materials

To establish the quantitative relationship between percussion drilling parameters and rock hardness, 12 rocks (Fig. 2(a)) were identified and preliminarily selected through scratches by using hardness tester, and those selected rock specimens with a length, width, and height of 2 m, 1 m, and 1 m were numbered A–M (Fig. 2(b)). Gneiss, marble, quartzite, and dolomite were all included in the rock specimens, and rocks with the same lithology (rock specimens B and D) were chosen in mines with varied buried depths to keep their hardness different. During percussion drilling tests, boreholes were perpendicular to surfaces of rock specimens (Fig. 2(c)).

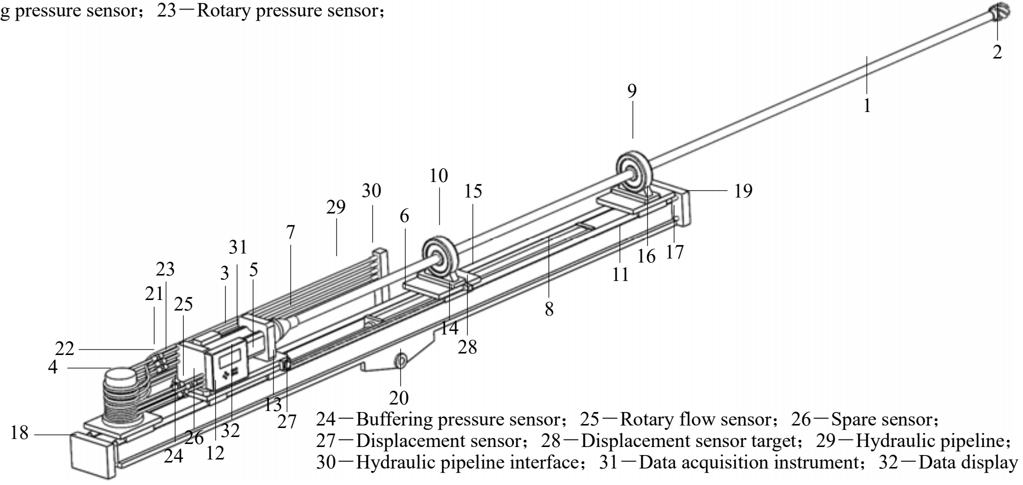
2.3 Test scheme

2.3.1 Weighted rock hardness

The information of rock structure and microscopic mineral distribution was examined by scanning electron microscope (SEM), and the mineral composition percentages in rock specimens were figured out by Ultima IV standard automatic X-ray powder diffractometer. According to the SEM (Fig. 3(a)) and X-ray diffraction (XRD) results (Fig. 3(b)) of rock A (results of the other rocks are not displayed for space), rock A is coarse–medium biotite granitic gneiss with gneissic structure, and it is composed of quartz, potash feldspar, plagioclase, and mica (Table 1).

Statistical investigation into mineral compositions of rocks were conducted, and the weighted hardness of rock minerals $H^{[8]}$ was calculated using Eq. (1) and listed in Table 2.

1—Drill rod; 2—Drill bit; 3—Rock drill; 4—Hydraulic drum; 5—Rock drilling platform tray; 6—Propeller; 7—Propelling rod; 8—Guide rail; 9—Front drill clamp; 10—Middle drill bracket; 11—Aluminum alloy beam; 12—Rock drill support plate; 13—Rock drill support plate slider; 14—Support plate for middle drill bracket; 15—Support plate slider for middle drill bracket; 16—Support plate for front drill clamp; 17—Support plate slider for front drill clamp; 18—Tail guard assembly; 19—Front guard assembly; 20—Rock drilling jumbo link; 21—Percussion pressure sensor; 22—Propelling pressure sensor; 23—Rotary pressure sensor;



24—Buffering pressure sensor; 25—Rotary flow sensor; 26—Spare sensor; 27—Displacement sensor; 28—Displacement sensor target; 29—Hydraulic pipeline; 30—Hydraulic pipeline interface; 31—Data acquisition instrument; 32—Data display

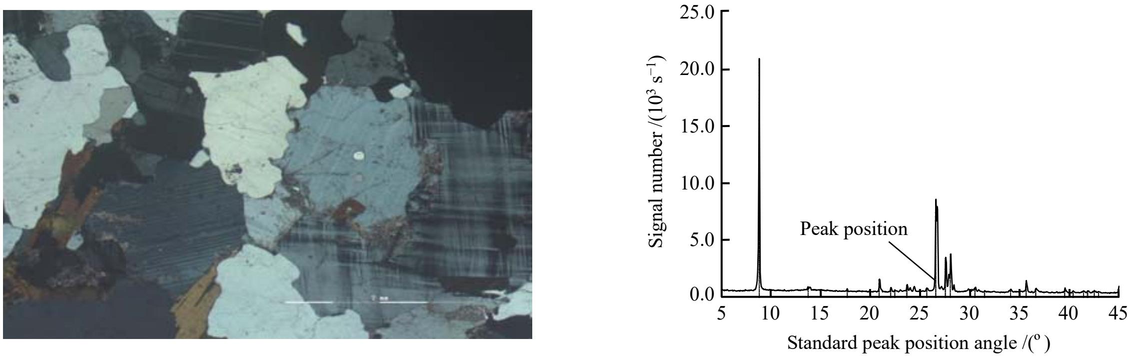
(a) Principles for digital monitoring of drilling process

(b) Laboratory tests for percussion drilling

Fig. 1 Digital monitoring of drilling process and laboratory tests for percussion drilling

(a) Rock specimens with a diameter of 5 cm (b) 12 rocks with a length, width, and height of 2 m, 1 m, and 1 m (c) Boreholes in percussion drilling tests

Fig. 2 Test materials



(a) SEM image (b) X-ray powder diffraction pattern

Fig. 3 SEM and XRD results of rock A

Table 1 Mineral composition analysis results of rock A

Mineral	Content /%	Hardness	Mineral	Content /%	Hardness
Quartz (Qtz)	24.6	7.0	Plagioclase (Ab)	35.4	6.0
Potash feldspar (Kfs)	22.6	6.0	Mica (Ms)	17.4	2.5

Table 2 Structure and weighted hardness of rocks

Number	Name	Structure	Weighted hardness
A	Coarse–medium grained biotite granitic gneiss	Gneissic	5.64
B	Fine grained quartzite	Block	6.90
C	Micro–fine grained calcite marble	Weak orientation	3.10
D	Fine grained quartzite	Block	6.97
E	Fine–micro grained granular calcite marble	Weak orientation	3.06
F	Micro–fine grained calcite marble	Weak orientation	3.02
G	Marbleized oolitic dolomite	Block	3.75
H	Medium grained biotite granitic gneiss	Gneissic	5.56
I	Flake micro–fine grained calcite marble	Flake	3.06
K	Medium–fine grained calcite marble	Block	3.01
L	Marbleized oolitic dolomite	Block	3.77
M	Medium–fine grained biotite granitic gneiss	Gneissic	5.89

$$H=\sum_{i=1}^{n}H_i\times n_i \tag{1}$$

where H_i is the hardness of the ith mineral and n_i is the percentage content of the ith mineral (%).

2.3.2 Percussion drilling tests

The parameters directly affecting percussion drilling speed and efficiency in drilling processes[15] are propelling pressure P_{r}, percussion pressure P_{e}, and rotational speed of drill rod N. To consider the influence of drilling parameters on impact energy dissipation in percussion drilling tests, three series of tests for pairwise variables of (a) propelling pressure and percussion pressure, (b) propelling pressure and rotational speed of drill rod, and (c) percussion pressure and rotational speed of drill rod were performed, and the parameter settings are given in Table 3. The polycrystalline diamond compact bits with a diameter of 45 mm were adopted in the tests.

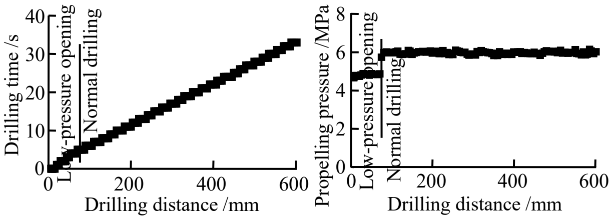
Table 3 Percussion drilling test parameters

Category	Propelling pressure P_{r} /MPa	Percussion pressure P_{e} /MPa	Rotational speed of drill rod N /(r • min^{-1})
Minimum	5.5	14.5	180
Increment	0.5	0.5	20
Maximum	8.5	17.5	280

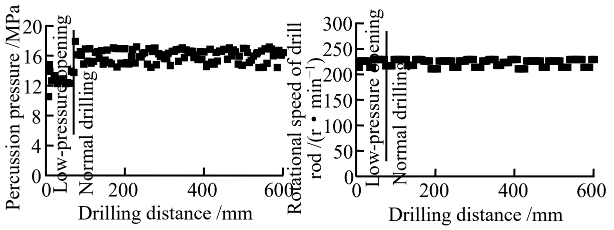
Note: the grade of propelling pressure, percussion pressure, and rotational speed of drill rod are 7, 7, and 6.

2.4 Standard data and database

The standard database of 12 rock drilling was obtained through tests, and the typical standard data of a single borehole obtained during percussion drilling is illustrated in Fig. 4. Percussion drilling is divided into two stages of low-pressure opening and normal drilling. At the stage of normal drilling, the drilling time has linear relationship with drilling distance, from which the drilling velocity V can be derived, the propelling pressure is stable at 6.0 MPa, the percussion pressure fluctuates around the set value (16.0 MPa), and the average rotational speed is 223.3 r /min.



(a) Drilling time (b) Propelling pressure



(c) Percussion pressure (d) Rotational speed of drill rod

Fig. 4 Typical data of percussion drilling test

3 Impact energy dissipation and influence factors

3.1 Impact energy dissipation calculation

Hydraulic percussion drill converts hydraulic energy into piston percussion energy, and then transmits the energy to rock masses in the form of stress waves through drill rod to realize rock fragmentation. According to the wave theory of drill rod, the impact energy E_{p}[18] is calculated as

$$E_{\mathrm{p}}=\frac{AC}{E}\int_0^{\tau}\sigma^2\mathrm{d}t \tag{2}$$

where A is the cross-sectional area (m^2) of the drill rod; C is the stress wave velocity (m /s); σ is the stress of drill rod (MPa), $\sigma=\gamma P_{\mathrm{e}}$, where γ is the stress conversion factor; t is drilling time (ms); τ is the pulse duration (ms); and E is the elastic modulus of drill rod (GPa). The performance parameters of percussion drill used in the tests are concluded in Table 4.

As shown in Fig. 5, the stress wave induced by percussion drilling is nearly rectangular[19] and can be simplified as rectangular wave to calculate single impact energy, so

Table 4 Main performance parameters of percussion drill

Cross-sectional area of drill rod A /m^2	Stress wave velocity C /(m • s^{-1})	Percussion frequency f /Hz	Energy transfer efficiency η_e /%	Pulse duration τ /ms	Elastic modulus of drill rod E /GPa
0.000 96	5 000	60	62.5	1	207

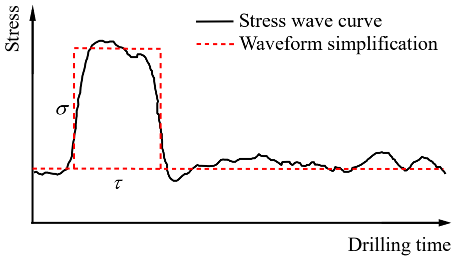


Fig. 5 Diagram of stress wave for percussion drilling

Eq. (2) can be expressed as

$$E_p = \frac{AC}{E}\sigma^2\tau \tag{3}$$

Part of the impact energy is transferred to break rocks, and the actual impact energy dissipation E_s is

$$E_s = \eta_e n_e E_P \tag{4}$$

where η_e is the energy transfer efficiency (%) and n_e is the number of impacts.

Therefore, the impact energy dissipation per unit length E_c is

$$E_c = \frac{\eta_e E_p f}{V} \tag{5}$$

3.2 Influence of drilling parameters on impact energy dissipation

The test results show that the impact energy dissipation per unit length decreases gradually with the increase of propelling pressure during drilling, and the relationships between them are basically linear (Fig. 6). For rock A, when P_r increases from 5.6 MPa to 8.3 MPa, E_c decreases from 213.1 kJ /m to 141.3 kJ /m, the change rate of E_c is 33.7%. During actual drilling, the impact efficiency is often improved by increasing the propelling pressure, but the drill rod may buckle and be damaged abnormally if the propelling pressure is too high. The impact energy dissipation per unit length for various rocks is a first-order function of the propelling pressure when the propelling pressure is in a reasonable range.

Figure 7 shows the relationships between percussion pressure and impact energy dissipation per unit length in rock drilling test. As P_e rises, E_c first declines and then rises, which accords with the trend of an open upward parabola. Although the corresponding curvature radii for various rocks are varied, the symmetry axes are basically around 15.7 MPa, and the optimal percussion pressure can be considered at the symmetry axis from the perspective of impact energy dissipation alone. The percussion pressure has a significant effect on drilling energy dissipation. For rock M, P_e grows from 14.9 MPa to 15.8 MPa, with a change rate of only 6.0%, while E_c declines by 22.2%. Therefore, the percussion pressure must be considered when analyzing drilling energy dissipation.

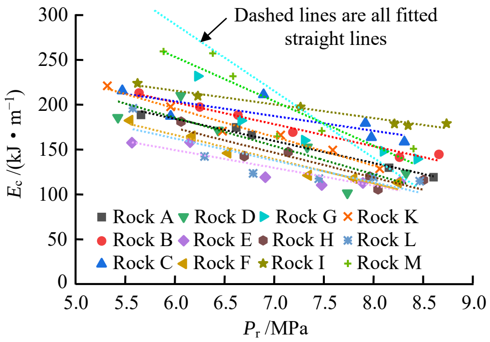


Fig. 6 Relationships between P_r and E_c for various rocks

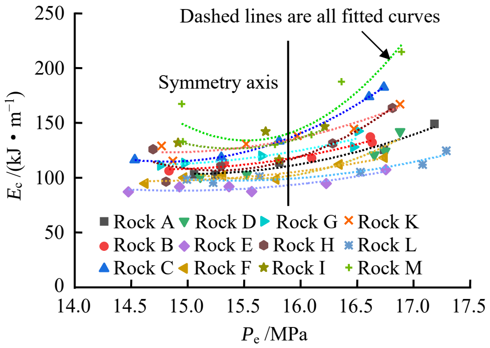


Fig. 7 Relationships between P_e and E_c for various rocks

For geological drilling rigs that rely on rotary cutting to break rocks, the rotational speed of drill rod has significant influence on rock breaking efficiency[11], while the measured results of percussion drilling tests show that the rotational speed of drill rod has little influence on impact energy dissipation (Fig. 8) and drilling speed.

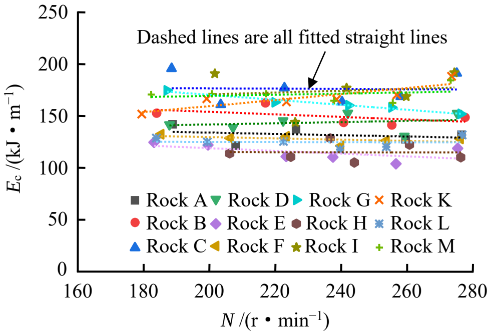


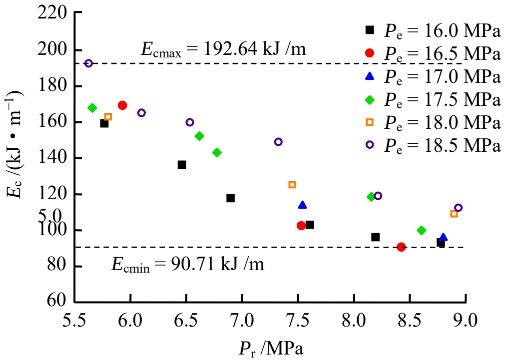
Fig. 8 Relationships between N and E_c for various rocks

Drilling energy ultimately comes from impact energy and propelling energy, and the reasonable rotational speed of drill rod primarily assists drill teeth to adjust rock breaking angle and prevent drill sticking. Therefore, to highlight the key factors, the influence of rotational speed of drill rod on impact energy dissipation will not be considered in subsequent data analysis.

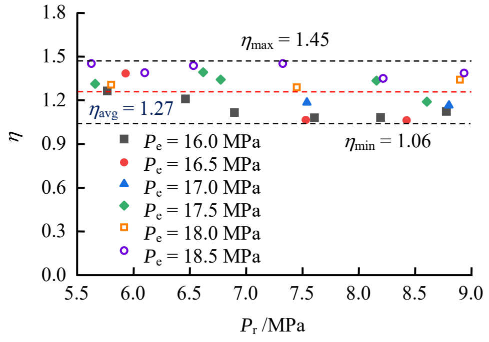
4 Mapping relationship between impact energy dissipation index and rock hardness

4.1 Definition of impact energy dissipation index

The drilling test results demonstrate that the impact energy dissipation per unit volume is affected by propelling pressure and percussion pressure (Fig. 9(a)), and the impact energy dissipation has strong discreteness. It is not accurate to directly establish the correlation between energy dissipation and rock parameters in exiting studies[13].



(a) P_r, P_e and E_c



(b) P_r, P_e and η

Fig. 9 Correlations between percussion drilling parameters for different rocks

To establish the one-to-one mapping relationship between impact response information and rock hardness, it is necessary to filter out the influence of various factors on impact energy dissipation so as to confirm the unique value of comprehensive evaluation variable corresponding to specific rock hardness. Because of the linear relationship between propelling pressure and impact energy dissipation (Fig. 6) and the quadratic function relationship between propelling pressure and impact energy dissipation (Fig. 7), an impact energy dissipation index η is defined as

$$E_c = \eta \cdot f\left(P_r\right) \cdot f\left(P_e\right) \tag{6}$$

where $f(P_r)$ is a first-order function of P_r and E_c; $f(P_e)$ is a quadratic function of P_e and E_c.

The parameters E_c, P_r, and P_e obtained from various rock drilling tests were statistically analyzed, and multivariate function regression analysis was conducted through mathematical software Mathematica to obtain η :

$$\eta = E_c P_r^{-1}\left(P_e^2 - 29.3P_e + 228\right)^{-1} \tag{7}$$

For rock A (Fig. 9(b), the other rocks are not listed one by one for space), with the change of P_r and P_e, the maximum and minimum values of E_c are 192.6 kJ /m and 90.7 kJ /m, and their ratio is 2.12. However, the average value η_{avg} calculated by Eq. (7) is 1.27, and the ratio of maximum value η_{max} to minimum value η_{min} is only 1.37. The impact energy dissipation index has stronger aggregation and is more suitable for establishing a mapping relationship with rock hardness.

It should be pointed out that Eq. (7) is an empirical formula, not a theoretical formula, and the impact energy dissipation index η is a fitting coefficient obtained by multivariate function regression. As a result, η is a dimensionless parameter that is characterized by not considering the physical meaning, and it is conducive to simplifying the formula and realizing convenient calculation, making it easier to be popularized in engineering.

4.2 Correlation between impact energy dissipation index and rock hardness

The fitted curve between weighted hardness H and impact energy dissipation index η for various rocks is given in Fig. 10, and H and η show positive correlation (correlation coefficient R^2 is 0.758), and the functional relationship is

$$H = 7.07\ln\eta + 2.63 \tag{8}$$

Then, the response information from percussion drilling can be interpreted to obtain rock hardness, which provides a new way to quickly obtain rock hardness on engineering sites. Gneiss, marble, quartzite, and dolomite were adopted for drilling in this study, and the database can be continuously filled in the follow-up study to obtain more accurate fitting curves and calibration coefficients. The ideas and methods can provide reference for related research about intelligent sensing of rock parameters.

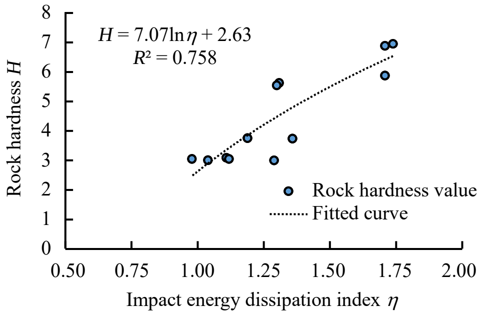


Fig. 10 Mapping relationship between α and H

4.3 Experimental verification

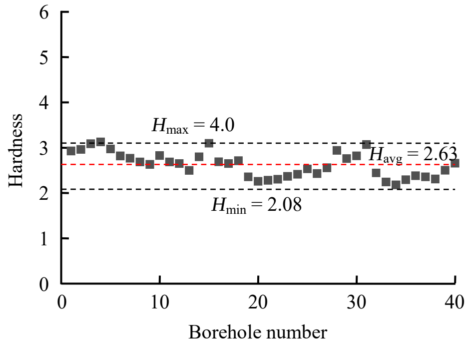
To verify the accuracy of the mapping relationship between the weighted hardness H and the impact energy dissipation index η, 40 boreholes were drilled using random combination of drilling parameters (propelling pressure, percussion pressure, and rotational speed).

For soft rocks, the cement blocks with an average hardness were poured, as shown in Fig. 11(a), the calculated average hardness value H_{avg} is 2.63, which is close to the measured value of 2.54. For hard rocks, the test results of granite is shown in Fig. 11(b). In Fig. 11(b), H_{avg} is 6.09, the minimum value $H_{\min}$ and the maximum value $H_{\max}$ are 5.49 and 6.89, which are consistent with the measured value of 6.20. Therefore, the impact energy dissipation index can better distinguish the characteristics of soft and hard rocks.

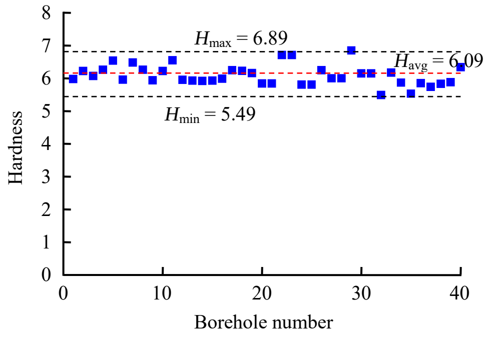
5 Engineering application

The practical application in railway tunnel engineering was carried out, and the surrounding rock of the tunnel is quartz schist, which is categorized as class II. The information during drilling process was monitored while drilling holes in the tunnel face (Fig. 12), and the rock hardness of the tunnel face was predicted to provide the basis for the prediction of charge and over/under-excavation.

By collecting data of percussion drilling displacement (Fig. 13(a)), propelling pressure (Fig. 13(b)), and percussion pressure (Fig. 13(c)), the impact energy dissipation (Fig. 13(d)) was calculated and analyzed, and the average rock hardness H_{avg} is 5.03 (Fig. 13(e)). Engineering application shows that rock parameters can be obtained without additional exploration or test by using the response information of drilling process in normal drilling construction, which provides a new idea for evaluating rock mass parameters on engineering sites.



(a) Hardness test of cement mortar



(b) Granite hardness test

Fig. 11 Hardness measurement and verification of cement mortar and granite

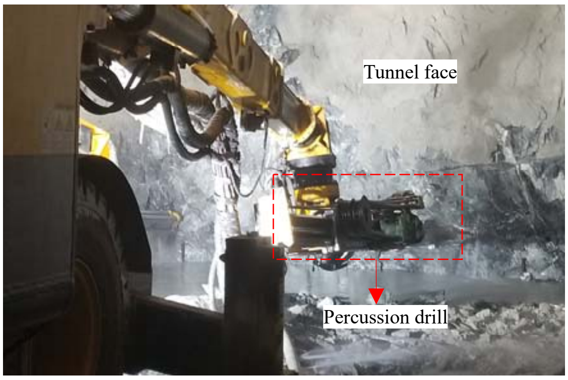
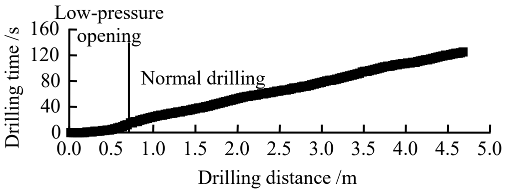


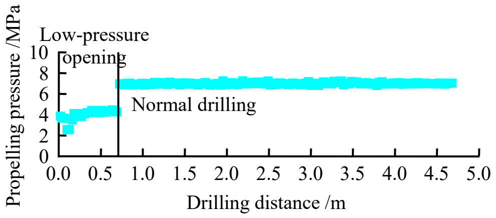
Fig. 12 Rock hardness measurement of tunnel face

6 Discussion

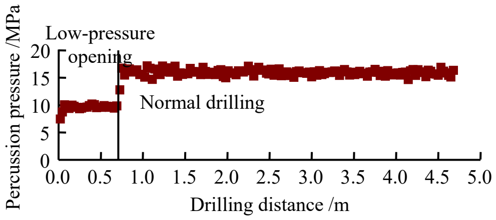
Rock hardness measurement and orthogonal tests of percussion drilling were parallelly performed, and the standard database of response information from drilling various rocks was established. The functional relationships between propelling pressure, percussion pressure, rotational speed, and impact energy dissipation were deeply explored, and the method of quantitatively evaluating rock hardness by using impact energy dissipation index was put forward, which is of great engineering application value. Although gneiss, marble, quartzite, and dolomite were used for tests, which are representative to some extent, all types of rocks are not covered[20], and the database still needs to be continuously filled in the follow-up study to obtain more accurate fitting curves and calibration coefficients. The present research object is rock, and the hardness of engineering rock mass will be affected by geological environment (in-situ stress, groundwater, and cracks)[21−22], which will be the future research direction of intelligent sensing on rock mass parameters.



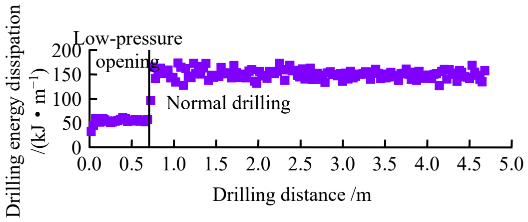
(a) Drilling time–drilling distance



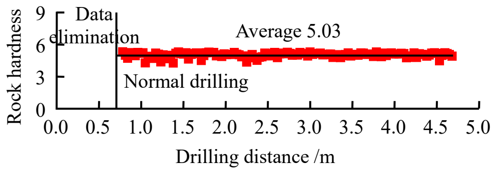
(b) Propelling pressure–drilling distance



(c) Percussion pressure–drilling distance



(d) Drilling energy dissipation–drilling distance



(e) Rock hardness–drilling distance

Fig. 13 A case of quantitative evaluation of rock hardness using percussion drilling

7 Conclusions

Based on a series of rock drilling tests, the variation law of drilling response parameters and the mapping relationship between drilling response parameters and rock parameters were revealed, and a quantitative evaluation method of rock hardness using impact energy dissipation index was developed. The main research results are as follows:

(1) There is a negative linear correlation between propelling pressure and impact energy dissipation. The fitting curve of percussion pressure and drilling energy dissipation is an open upward parabola, and the curves for various rocks have the same symmetry axis but different curvature radii. The influence of rotational speed of drill rod on drilling energy dissipation can be ignored.

(2) Through dimensionless treatment of drilling energy dissipation per unit volume, the influence of percussion drilling parameters is filtered out, and a new index used to characterize rock hardness is defined: impact energy dissipation index η, which has small discreteness and good correlation with rock hardness.

(3) The response information of conventional borehole drilling process can be obtained and interpreted using digital sensing technology, and rock hardness can be then measured without additional investigation or test, which can provide a new idea for rapid evaluation of rock mass parameters on engineering sites.

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