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Prediction of fracture frequency and RQD for the fractured rock mass using drilling logging data

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Abstract

Fractures in rock mass provide the dominant role in its mechanical properties. In this paper, an in situ experiment is carried out to investigate the specific energy of rock mass, from which the response of the specific energy on the open and in-filled fractures is analysed. The effect of the intact core and the open and in-filled fractures on the specific energy is studied, presenting the link between the fracture frequency and the specific energy. The result shows that the relationship between the fracture frequency and the specific energy is proposed for evaluating the fracture frequency and rock quality designation (RQD). A standard deviation of 0.18 for the specific energy can be used as a critical point to distinguish between the segment of the intact core and the fracture segment. A new prediction method is proposed to determinate the fracture frequency and RQD of rock mass, and its utilization for RQD prediction can overcome the limitations of the original RQD. This method is applied in the water conservancy project and demonstrated to be reliable and accurate by comparative studies with previous work, thus providing a low-cost and simple approach for rock quality evaluation.

Keywords Discontinuous fracture · RQD · Fracture frequency · Specific energy

Introduction

Deere (1963) introduced the concept of rock quality designation (RQD) to evaluate the quality of rock mass in 1963. The RQD has become a hot topic for all kinds of assessments of rock mass and is defined as (Deere et al. 1967; Deere and Deere 1988; Deere 1989)

$$\text{RQD} = \frac{\text{Length of core pieces} \geq 10 \text{ cm}}{\text{Total core run length}} \times 100 \qquad (1)$$

The RQD is an important index for rock mass classification, which has been accepted and used all over the world (Deere 1963; Bieniawski 1989). The calculation method of RQD has

been improved such as RQD_C (depends on the cumulative length of unbroken pieces and the number of unbroken pieces, Li et al. 2009), RQD_I (depends on the cumulative length of broken pieces, Azimian 2016), and $\text{RQD}_{M\text{-WJD}}$ (considering the fractured zone, Haftani et al. 2016). Due to its very low cost, ease of use, and reproducibility, RQD determination generally is used for various rock engineering applications, such as tunnelling, mining, and cavern engineering (Haftani et al. 2016; Wang et al. 2018a; Wang et al. 2018b; Jiang et al. 2021a, b). The RQD has become a standard practice for all kinds of geotechnical investigations (Azimian 2016). As an early warning for low-quality rock mass that may need greater scrutiny or other additional investigation, it is widely used to provide an initial reference and guidance from a data source for design decisions in rock engineering (Haftani et al. 2016), such as determination of rock quality for large riprap or concrete aggregate in quarries, iidentification of potential problems in relation to bearing capacity and sliding in rock foundations, warning indicator of low-quality rock zones, determination of the shear strength (Barton 1990; Goodman 1993) and rock mass strength and modulus of elasticity (Zhang and Einstein 2004), and rock mass classification systems, e.g. the RMR-system, GSI-system (Hoek 1994), and Q-system (Barton 2002; Bieniawski 1989).

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Various empirical methods have been proposed to estimate the engineering properties of rock mass based on rock mass classification systems such as RQD-system (Deere et al. 1967; Coon and Merritt 1970; Serafim and Pereira 1983; Zhang and Einstein 2004; Zhang 2010; Zheng et al. 2018; Zheng et al. 2020), RMR-system (Bieniawski 1978; Yudhbir and Prinzl 1983; Nicholson and Bieniawski 1980; Mitri et al. 1994; Sheorey 1997; Aydan and Dalgic 1998), Q-system (Barton et al. 1980; Barton 2002), and GSI-system (Hoek and Brown 1997; Gokceoglu et al. 2003; Hoek and Diederichs 2006). Considering its worldwide usage in the Q-classification system and the RMR-classification system, the RQD is considered a practical parameter, especially when the RMR is used to obtain the GSI. The RQD has also been quickly developed to determine the mechanical parameters of a rock mass, so that it has become one of the important parameters of rock mass in rock engineering (Hoek and Bray 1981; Hoek and Brown 1980). The value of RQD is usually influenced by a variety of limitations and factors including the borehole orientation, the core size effect, and the selected threshold value (Harrison 1999; Hack 2002; Chen et al. 2005). Accordingly, many methods have been proposed to remove these limitations, such as the volumetric joint density (Palmstrom 1982, 1985, 1986; Sen and Eissa 1992), the cumulative core index (Sen 1990), the weighted joint density (Palmstrom 1995, 2005), and the improved RQD (Li et al. 2009; Azimian 2016; Zhen et al. 2018). However, these previous methods are not widely applied in rock engineering. Although the RQD index has currently become a basic parameter for rock engineering due to its easy determination and application at a very low cost (Hoek and Bray 1981; Hoek and Brown 1980), it is usually affected by many factors of rock mass including the strength properties, the core size effect, the joint orientation, the drilling direction, and the joint roughness (Azimian 2016; Choi and Park 2004). According to its definition, a significant limitation of the rock quality designation is the restriction on the measurement consistency as a result of the effect of the selected threshold value (Hack 2002; Chen et al. 2005; Azimian 2016) or the low-quality rock segment including the broken piece, core washed, and crushed segments (Araghi et al. 2006; Azimian 2016). The following limitations restrict the application of RQD (Choi and Park 2004; Palmstrom 2005).

– The different RQD values are produced due to the effect of the different threshold lengths, even a ±0.001 m changing in the selected threshold value of 0.1 m (Azimian 2016).
– The RQD value is greatly influenced by the joint orientation and the coring direction (Palmstrom 1995, 2005; Haftani et al. 2016; Azimian 2016).

– The RQD provides no description of the rock quality in length of <0.1 m along the scanlines (Palmstrom 1995, 2005; Bieniawski 1989).

Although some scholars make effects to remove the limitation of the threshold value on the determination of RQD (Araghi et al. 2004; Azimian 2016), the lengths of the weak segments became a limitation, which is associated with the determination of ROD due to the inadequate description of the broken piece, core washed, and karstic and crushed segments. Hence, a new method would be valuable to obtain a realistic and reliable impression of RQD.

This work aims to present an in situ experimental investigation of the drilling logging data and specific energy of intact rock and fractured rock mass, from which the response characteristics of the specific energy on the open and in-filled fracture is analysed. A new, straightforward method for the determination of fracture frequency using specific energy in a borehole is proposed to implement the RQD prediction without being affected by the various limitations of the original RQD. A comparative study with previous work is performed to verify the reliability of the proposed method in an engineering application.

Engineering background, test equipment and test plan

Engineering background

The drilling tests were conducted in the Daheba hydropower station, which is located in the Ziwu River in the Qinling Mountains of China. The Ziwu River cuts deeply into the rocky ground and forms a U-shaped valley. The geomorphology of the tested area consists mainly of deep valleys flanked by steep, deep valleys. The surrounding rocks consist mainly of diorite, granite, and crystalline limestone, and the fresh hard rock blocks have good integrity and massive texture. There are localized zones of weakening in the limestone and marble that include fractures, nodules, lumps, and flakes, but no Cartier features are visible in the limestone. The rocks in the area show slight weathering. The joint wall surfaces are mostly straight and rough. Most joint surfaces are cracked and do not show evidence of filling. A few sections of the joint surfaces host gouge material consisting mainly of calcite and finely crushed (clay to silty) rock particles. The three groups and four groups of joints are usually observed along most of the tunnel.

Testing equipment

To investigate the relation of the drilling logging data to the fracture frequency and RQD, we have developed a drilling

process monitoring (DPM) system for rock mass in situ (Fig. 1). The DPM mainly consists of five implements (Fig. 2): the loading system of thrust force, the torsional driving system, the monitoring system of drilling logging data, the control system, and the processing system of drilling logging data. When performing rock mass drilling tests, the power unit of this system with a maximum power of 90 kW is used to provide the rotational speed range of 0~1000 rpm, a torque range of 0~2458 N·m, a penetration rate range of 0~20 mm/min, and a thrust force range of 0~18 kN. The performance parameters, including rotational speed, torque, penetration rate, and thrust force, is larger than those by Yue et al. (2004) and Wang et al. (2019). It can control any of the four drilling performance parameters, including the drilling force, the drilling rate, the rotation speed, and the torque and monitor the variation of the drilling parameters versus borehole depth along the scanlines during drilling. The acquisition and processing system can collect 0~500 sets of drilling logging data per second, which can save the recorded data in the Excel file.

The diagram of the torque and drilling force at different penetrations per revolutions for intact marble is presented in Fig. 3. The relationship between the obtained torque and the drilling force is observed for a repeated experiment. As shown, the obtained results are slightly scattered, due to a lack of homogeneity in the marble, and remain within a specific range. An impregnated diamond bit is used in the drilling process monitoring (Fig. 2).

Test plan

The drilling tests are carried out to obtain the drilling logging data, including the rotation speed, torque force, penetration rate, thrust force, and penetration depth per rotation in the field. The penetration rates of drilling were selected in the range of 0.1–1.2 mm/min. The rotation speeds were selected

in the range of 200–600 rpm. To protect the testing system, rotation speeds were controlled to be greater than 200 rpm when the penetration rate exceeded 1 mm/min.

Drilling data responses to fractures

Drilling data responses to the rock fracture when drilling through fracture zones have been investigated by many scholars (Barr 1984; Pfister 1985; Scoble and Peck 1987; Schunnesson 1990, 1996). The results demonstrated that the RQD value and the fracture logs from scanline coring would offer a reliable evaluation of rock mass quality (Scoble and Peck 1987). Pfister (1985) and Schunnesson (1990) also showed that the detailed responses of the drilling data demonstrate many typical features for rock fractures using the artificial fractured rock in the laboratory.

When the diamond bit drills through a fracture zone in the length range from 0 to 2 m without being filled, the data of torque, as well as the drilling force and penetration rate, increase in the discontinuous fracture zone and largely fluctuate in the length range from 0 to 0.9 m as shown in Fig. 4. When drilling through a single open fracture as shown in the length range from 1.2 to 1.8 m, a drop in the torque and the drilling force is found in the void. Then, the drop is followed by a rapid decrease over the void, reaching nearly zero. In contrast, the penetration rate is also influenced and peaks simultaneously and has a sharp increase in a single fracture. The two examples show that the penetration rate, drilling force, and penetration rate are strongly and obviously influenced by the rock fracturing without in-filling.

Figure 5 shows one of the in-filled fractures when penetrated by the drill bit. The bit drills through an in-filled fracture zone in the length range from 0.2 to 1.2 m. In the central part, it is noted that the torque between 0.47 and 0.53 m, as well as the penetration rate and drilling force, increases in the single fracture. The example shows that the drilling force and penetration rate are also strongly influenced by the rock fracturing when in-filled.
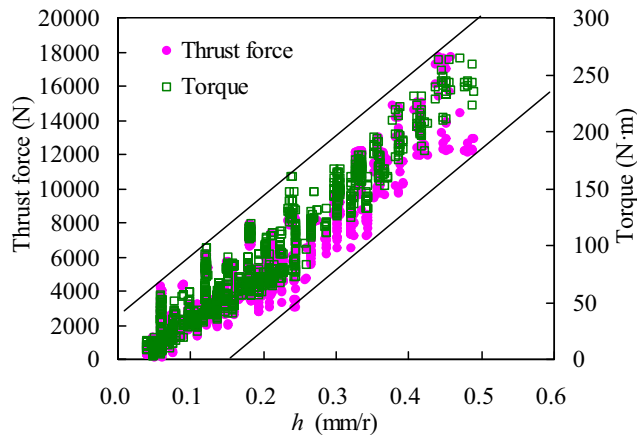
Figure 5 also shows clearly that the torque and penetration rate peak in a discontinuous fracture zone with in-filling as shown in the length range from 1.11 to 1.2 m, and the drilling force has a tendency to slowly decrease. In addition, the value of the torque and drilling force is more scattered than that in the length range of the intact core. This indicates that the scattered characteristics of drilling force and the torque data can be used to distinguish a fracture zone with in-fill. This finding implies that when many in-filled and open fractures interact, the response characteristics of the drilling parameters become much more complicated. In Figs. 4 and 5, an increased drilling force and penetration rate are observed in a fracture zones. However, the penetration rate and drilling force decrease at the same time as the torque peaks in the

Fig. 1 Drilling process monitoring system (DPM)

Wireless transmitters of thrust force -on-bit

Wireless transmitters of torque-on-bit

XCY-1型 岩体力学参数 旋切触探
西安理工大学设计研发 陕西西探地质装备有限公司制

Fig. 2 Schematic drawing of DPM for rock mass. (1) Power unit, (2) frame and chassis, (3) control system, (4) power head, (5) console, (6) bottom bracket, (7) tilting mechanism, (8) pillar, (9) holder, (10) holder, (11) motor cover, (12) power head carriage, (13) hydraulic oil tank, (14) shield, (15) radiator, (16) drill bit
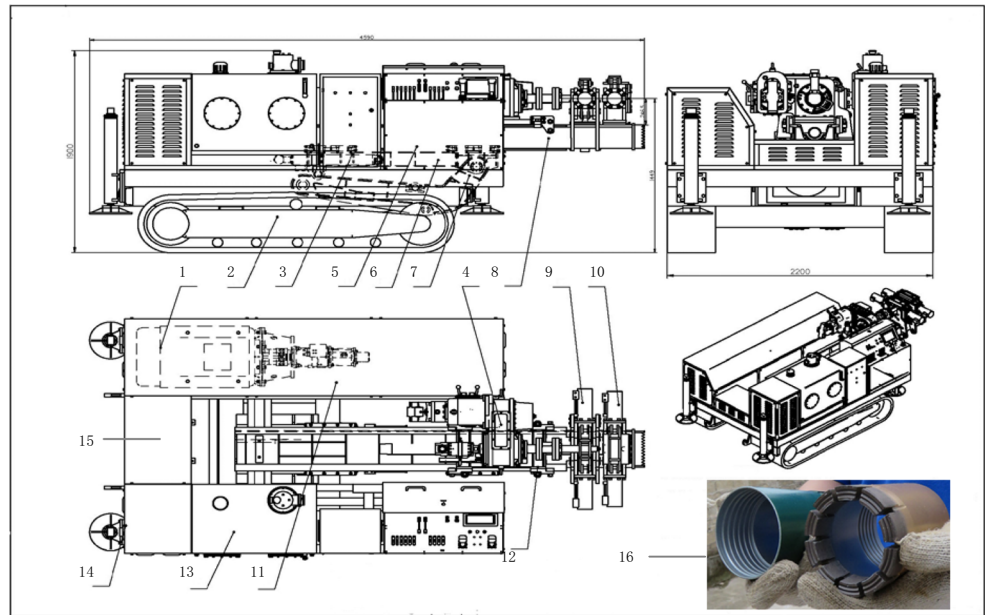
fracture zone, indicating the possibility of a stall in the drill string due to strong fracturing.

The variability in the drill performance parameters follows the fractures or fracture zones where the scattered drilling parameters can be observed. The scatter and variability of the drilling force, penetration rate, and torque are associated with the fractures. In a single open fracture, the torque and drilling force usually show a negative peak due to the decrease in the resistance to rotation of the drill bit for a short time. In an in-filled fracture, the increasing of the resistance to rotation generally results in an increasing in the rotation torque. When the fracture is in-filled, the fillers dampen response of drilling force, usually resulting in less variation of the drilling force. This finding suggests that the torque and drilling force are always more scattered when within the length range of the fracture, implying that the discrete of the drilling parameters may be used to distinguish the fracture zone from the intact core range.

In summary, the variability and magnitude of the drilling force, torque, and penetration rate are affected by fractures. However, the complicated correlation for each drill performance parameter can change depending on the properties of the rock mass. Furthermore, the scattered effects of each

Fig. 3 Measured thrust force and torque versus penetration per revolution in drilling test on marble with different repetitions
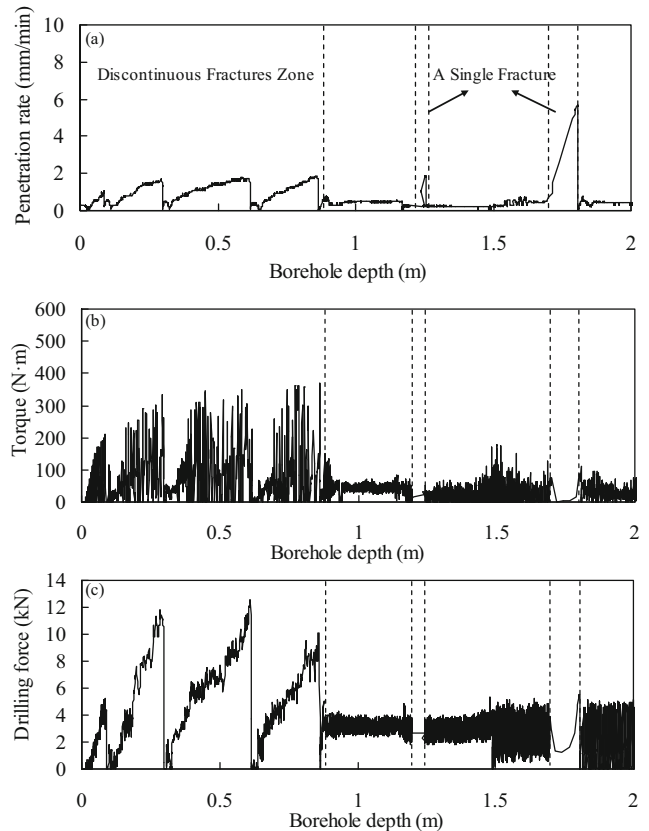
Fig. 4 Response of drilling logging data to the fracture zone without being filled. (**a**) penetration rate; (**b**) Torque; (**c**) drilling force
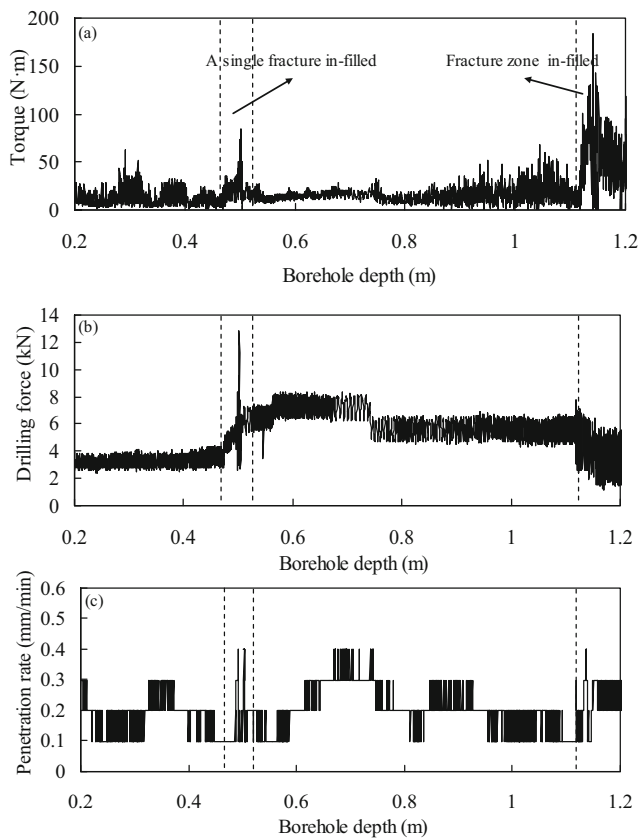
Fig. 5 Response of drilling logging data to the fracture zone in-filled. (**a**) torque; (**b**) drilling force; (**c**) penetration rate

parameter, in a certain length, are also relevant to various fractures and fracture zones. It is likely that the scattered effects of the drill performance parameters can provide more information about rock mass for the determination of RQD.

Specific energy response to open and in-filled fractures

First introduced by Teale (1965), the specific energy has been accepted as an important parameter to evaluate the drillability and mechanical properties of rock in rock engineering and is expressed as

$$e = \frac{F}{A} + \frac{2\pi Mw}{Av} \tag{2}$$

where M is the torque (N·m); w is the rotation speed (rpd); F is the drilling force (N); e is the specific energy (N/mm^2); v is the penetration rate (mm/min); and A is the excavation area (mm^2). The penetration depth of per-rotation during drilling is expressed as

$$h = \frac{60v}{w} \tag{3}$$

where h is the penetration depth of per-rotation during drilling. According to Eqs. (2) and (3), the specific energy is expressed as

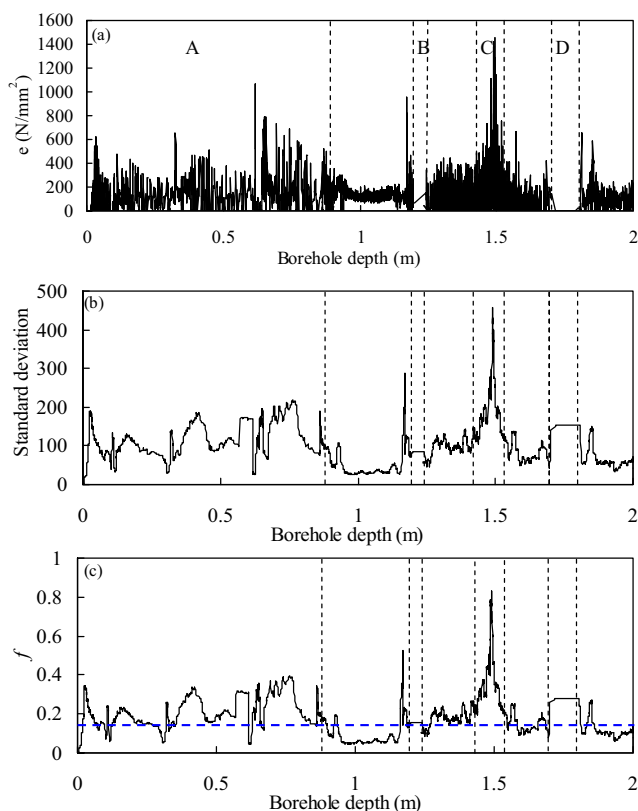$$e = \frac{F}{A} + \frac{\pi M}{30Ah} \tag{4}$$

The rotary drilling tests are carried out on three different rocks using an impregnated diamond bit, and the specific energy plotted against penetration per revolution is obtained as shown in Fig. 6. The values of the specific energy of limestone, marble, and sandstone are distributed evenly between 246.3 and 350.2 N/mm^2, 118.7 and 199.4 N/mm^2, and 40.9 and 94 N/mm^2, respectively. There are many similar studies of Pennant sandstone, sandy shale, sandstone, and concrete about the finding in the literature (Teale 1965). No relationship is presented between the specific energy and the penetration depth per revolution (Teale 1965). Figure 6 also shows similar results of the experiments in both the tuff and marble. The obtained data of specific energy is slightly scattered due to the less homogeneous tuff and marble. The values of penetration per revolution present the minor differences, which show that the specific energy may be constant for intact rock, and it is immune to the drilling logging data.

The experimental results (Teale 1965) show that the distribution of the specific energy in the less homogeneous shale is more scattered than that in the intact rock, which is caused by the zones of weakness. This suggests that the distribution characteristics of the specific energy can be used to determine the length of core piece of rock mass. The drilling tests are performed on the intact rock and the open and in-filled fracture segment of rock mass using an impregnated diamond bit. In Fig. 4, the response of the drilling force and penetration rate is more obvious to the fracture zone without being filled than that of the torque. The drilling force and penetration rate tend to influence the specific energy in the most significant manner for an open fracture. In Fig. 5, the torque and drilling force is
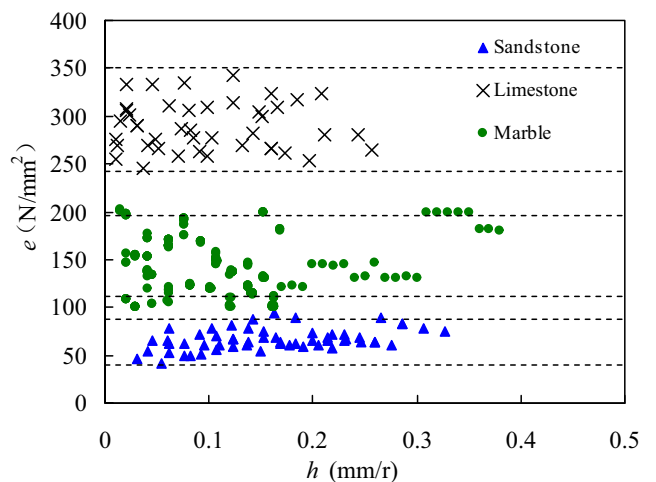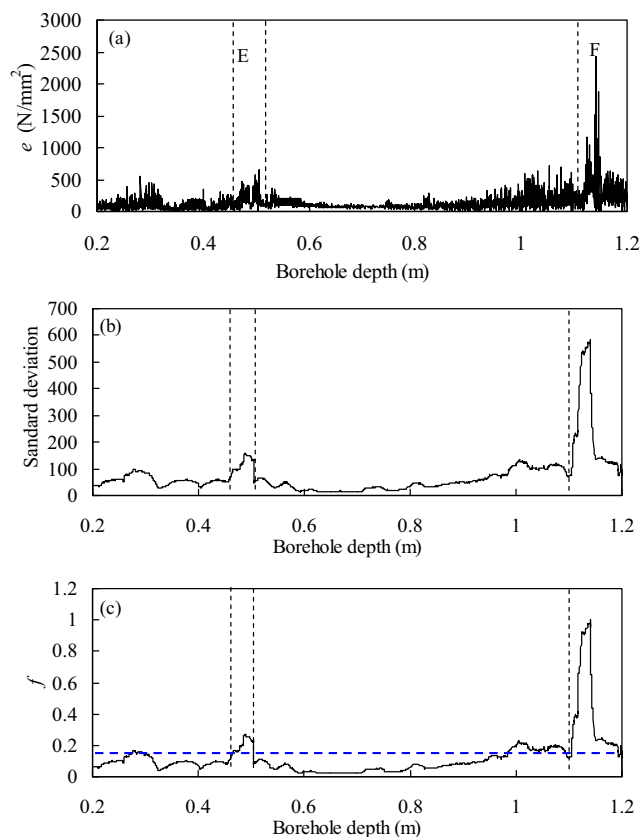

Fig. 6 The value of e and h for different rocks

larger fluctuating than the penetration rate. The torque and drilling force influence the specific energy in the most significant manner for an in-filled fracture. This shows that the penetration rate influences the specific energy in a least manner for an open and in-filled fracture. The variability of specific energy along the borehole is shown in Fig. 7. Figure 7 a shows the results from 'tuff broken pieces' using an impregnated diamond bit. The variability of specific energy in the length range from 0 to 0.86 m (segment A) is more scattered than those of intact tuff in the length range from 0.86 to 1.2 m and from 1.5 to 1.7 m, due to the presence of discontinuity such as the broken pieces and open fractures. In the process of the drilling through the open fracture, the specific energy of the open fracture is in the void and its value is zero as shown in the segment of B and D. The lengths are 0.171 m and 0.152 m in the segment of B and D, respectively, which is consistent with the results obtained by using the drilling data in 'Specific energy response to open and in-filled fractures'. The specific energy for the in-filled fracture is also influenced and peaks simultaneously with the torque and drilling force peaks in the discontinuous in-filled fracture zone in the length range of F (in Fig. 8) and has a sharp increase over the fill in segments C (in Fig. 7) and E (in Fig. 8) of the single fracture. The results show that the specific energy along the borehole is strongly dependent on the open and in-filled fracture. In addition, in the fractures and fracture zones, the scattered effects of the

Fig. 8 Response of specific energy during the penetration of the in-filled fracture zone. (**a**) specific energy; (**b**) standard deviation; (**c**) the value of f

variability of specific energy are observed. The scatter of the specific energy is related to the fracture due to the heterogeneity and discontinuity of the rock mass. Figures 7b and 8b show that the open and the in-filled fractures, respectively, correspond to the standard deviation for different length ranges. The difference between the fracture and the intact rock is studied with about the standard deviation of the specific energy against the borehole length. The standard deviation of specific energy (>50) for both the open and in-filled fracture is greater than that of intact core (<50). This suggests that a major difference in the standard deviation between the fracture and intact rock may be regarded as a classification criterion for the rock mass.

A data normalization method for the standard deviation is used to describe the scattered effects of the specific energy as follows

$$f = \frac{s - s_{min}}{s_{max} - s_{min}} \tag{5}$$

where f is the standard deviation of the specific energy, s_{min} is the minimum value of the standard deviation, and s_{max} is the maximum value of the standard deviation. The difference of maximum and minimum standard deviations in Eq. (5) has great variance for different boreholes and is not an intrinsic property of the boreholes and RQD. The difference can reflect

Fig. 7 Response of specific energy during the penetration of the open fracture zone. (**a**) specific energy; (**b**) standard deviation; (**c**) the value of f

the distributions of the open and in-filled fractures. Figures 7c and 8c illustrate the distributions of the specific energy for the open and in-filled fractures, respectively. Seeing the two figures, the data of the specific energy is presented in the length ranges of intact cores. The value in the intact cores is approximately less than 0.18, which implies that the f value is approximately less than 0.18 in the segment of intact cores, and the $f > 0.18$ in the broken and fracture segment in the length ranges of A, B, C, D, E, and F. Hence, the standard deviation of 0.18 is taken as a critical value to determine the ranges of fracture.

Determining the RQD using specific energy

Correlation between fracture frequency and specific energy

The fracture frequency can be determined as (Priest 1993)

$$\lambda = \sum_{i=1}^{N} \lambda_i \cos\theta_i \tag{6}$$

where λ is the fracture frequency, N is the fracture sets number, λ_i is the fracture frequency normal to set i, and θ_i is the fracture orientation.

The variation of the drilling parameters versus borehole depth along the scanlines is related to the fracture of rock mass during drilling (Barr 1984; Schunnesson 1990; Teale 1965). Due to the specific energy calculated by the drilling parameter, the specific energy can provide more information about the fracture (Scoble and Peck 1987). Since the quality of intact rock is better than that of fracture zones, the data points of specific energy of intact rock are less scattered than those of the fracture zones (Figs. 7 and 8). About 200 drilling tests were conducted to investigate the relationship between the specific energy and the fracture in different rock masses (tuff, marble, granite, and sandstone), which is related to the joints, fracture zones, and crushed zones. The correlation between the fracture frequency and the standard deviation is shown in Fig. 9. The results show that the higher fracture frequency is related to the higher standard deviation. The standard deviation is approximately linearly increased with an increasing in the fracture frequency. Hence, the fracture frequency using the standard deviation can be estimated as

$$\lambda = \varsigma s \tag{7}$$

where ς is the fitting parameter of relationship curve between the fracture frequency and the standard deviation of specific energy.
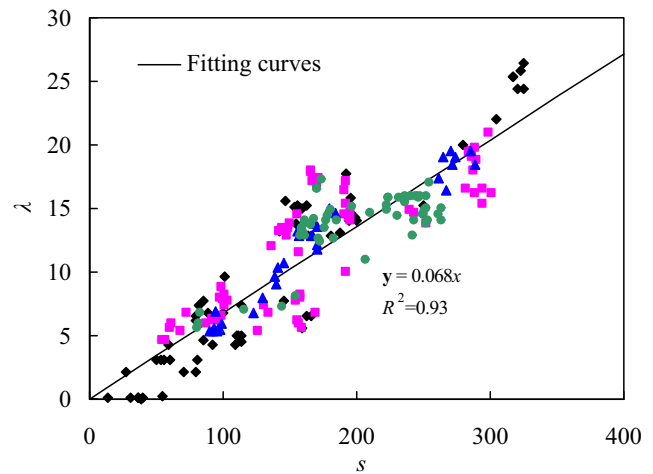

Fig. 9 The correlation between fracture frequency and standard deviation at different scanline length

Relationship between RQD and specific energy

The RQD index was established by Deere (1963) as a description of the rock mass quality in a borehole and defined as the percentage of a scanline consisting of spacing values greater than or equal to 10 cm. In addition to the straightforward approach for the RQD determination from scanline coring, various indirect approaches also offer available and acceptable coverage for the RQD evaluation. The determination procedure of the RQD is shown in references (Bieniawski 1989; Deere 1989; Azimian 2016).

The value of the RQD can also be calculated from the discontinuity fracture frequency measured from a borehole camera and a scanline core log. Relationships between the RQD and the fracture frequency have been derived for different distribution characteristics of the discontinuity spacing (Sen and Kazi 1984; Priest 1993; Sen 1993). The analytical relationship between the RQD and fracture frequency is derived by Priest and Hudson (1976):
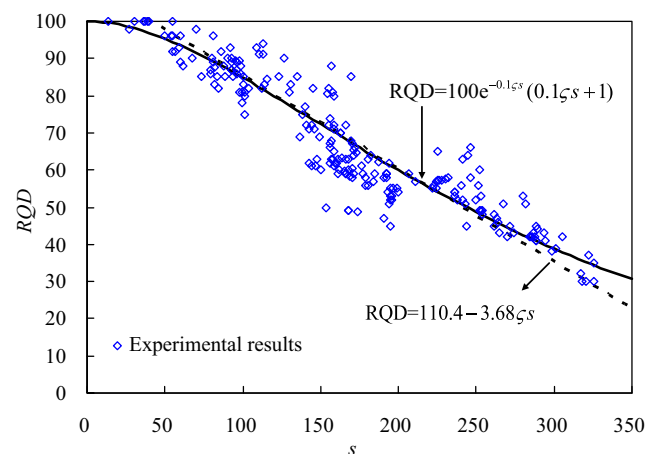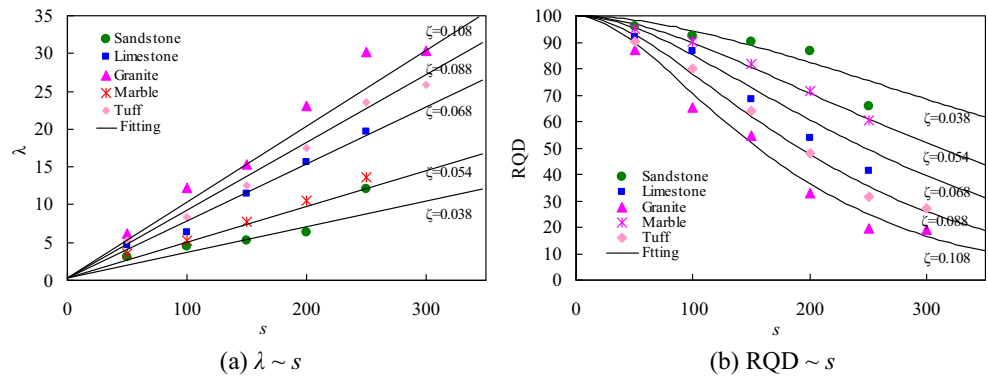

Fig. 10 Relationship between RQD and standard deviation

Fig. 11 The effect of ζ on λ and RQD. **a** $\lambda \sim s$. **b** RQD$\sim s$

$$RQD = 100e^{-\lambda t}(\lambda t + 1) \qquad (8)$$

where t is the selected threshold value, t=0.1 m. Equation (8) is written as

$$RQD = 100e^{-0.1\lambda}(0.1\lambda + 1) \qquad (9)$$

An approximate linear relation to the RQD values can be given as (Priest 1993):

$$RQD = 110.4 - 3.68\lambda \qquad (10)$$

The empirical relationship between the fracture frequency and RQD is proposed by Elci and Turk (2014):
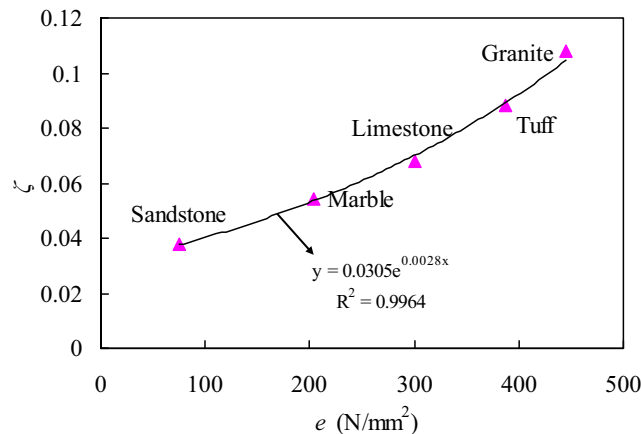
$$\lambda = ae^{bRQD} \qquad (11)$$

where a and b are fitting parameters.

Substituting Eq. (7) into Eq. (8) and Eq. (10), the RQD is calculated as

$$RQD = 100e^{-0.1\varsigma s}(0.1\varsigma s + 1) \qquad (12)$$
$$RQD = 110.4 - 3.68\varsigma s \qquad (13)$$

Figure 10 shows the relationship obtained by Priest and Hudson (1976) between the measured values of s and λ and the values calculated by Eq. (12) and Eq. (13).

The less effort and core logging time is required to estimate the value of RQD using the specific energy, while being easy to measure; therefore, this method makes it convenient to determine the value of RQD. Since the value of RQD is calculated using the value of s, which describes the spatial distribution of fracture zones, joints, and intact rocks along the scanlines, the obtained values of RQD are closer to real value. Although the method has a limitation of a dependence of the drilling direction, it also can provide more information about the characteristics of rock mass at the selected threshold length of <0.1 m.

The effect of ζ on the RQD

By taking 19 boreholes in different types of rock mass, which mainly contain sandstone (5 boreholes), granite (6 boreholes), tuff (2 boreholes), marble (1 borehole), and limestone (5 boreholes) from the Silurian period, the effect of ζ on the fracture frequency and the RQD is investigated. The values of ζ for granite, limestone, tuff, marble, and sandstone are obtained as shown in Fig. 11, and the values from the three types of rock mass are 0.038, 0.054 0.068, 0.88, and 0.108, respectively. As seen, the fracture frequency decreases with an increase in the value of ζ at the same value as s, but the RQD increases. Moreover, the value of ζ for granite is the largest, followed by that of limestone and then sandstone, due to the difference in the three types of rock, implying that the value of ζ only depends on the type of rock mass.

The correlation between the value of ζ and the specific energy e for granite, limestone, tuff, marble, and sandstone is shown in Fig. 12. With an increase in the specific energy e, the value of ζ increases. Therefore, to determine the value of ζ using specific energy, an empirical relationship between the ζ and specific energy can be given as

Fig. 12 The relationship between ζ and e

Fig. 13 The standard deviation *s* and *f* versus borehole depth in a drilling test
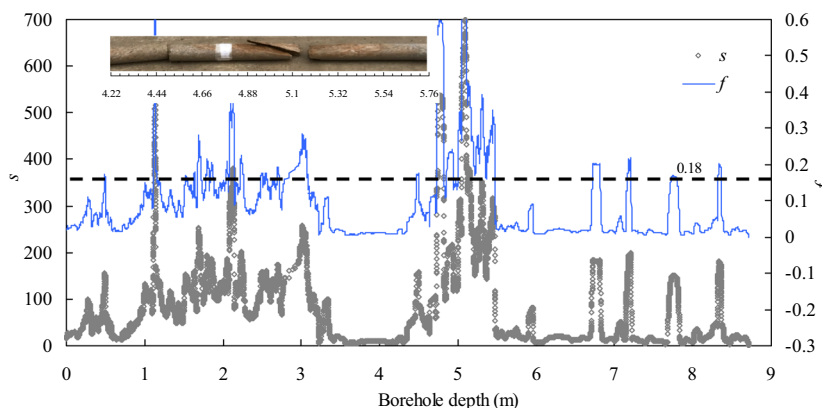
$$\varsigma = -0.0609\ln e + 0.3133 \tag{14}$$

where ζ is the fitting parameter of relationship curve between the fracture frequency and the standard deviation of specific energy and e is specific energy of rock. In this method, the value of ζ can be obtained simply during the drilling process.

Comparative studies with previous work

The drilling test was carried out to validate the reliability of the determination for the RQD value using the proposed method in rock engineering in a traffic tunnel. The observed fractures using the specific energy in jointed rock mass were compared with the cores logging. The proposed method was applied at the traffic tunnel to analyse the applicability of the RQD in rock engineering.

A 8.75-m borehole in the traffic tunnel was selected for the purposes of this work. After observations of specific energy, the core lengths from the proposed method in 'Determining the RQD using specific energy' were analysed by comparison with the length from the core logging as shown in Fig. 13. In the segment at 4.22~5.76 m, the borehole length is divided into the three segments of 0.22, 0.44, and 0.66 m. The value of the standard deviation for one segment is in the range of approximately less than 0.18 and that of two segments in the range of more than 0.18. After comparison, the obtained results using the proposed method are consistent with those from core logging.

The borehole, which is 8.75 m deep, was divided into 9 segments by units of 1 m in length. Using the proposed method (Eq. 12), the RQD values for each segment were obtained. As shown in Fig. 14, the RQD value in this work is slightly smaller than the value of RQD of Deere (1963) due to reducing the effect of the joint. The comparative study of the proposed method with the previous methods is carried out to

demonstrate the reliability. It can be observed in Table 1 that the RQD value from the proposed method is mostly at or slightly smaller than the values of Palmstrom (2005), Araghi et al. (2006) Azimian (2016), and Eq. (12), due to the effect of weak segments such as the broken piece, core washed, crushed, and fracture induced by drilling. Hence, the determined RQD using the specific energy tends to be a conservative estimation compared with the previous methods of Palmstrom (2005), Araghi et al. (2006), and Azimian (2016).

Conclusions

In this paper, an in situ experiment is carried out to investigate the specific energy of rock mass, from which the response of the drilling parameters on the open and in-filled fractures is analysed. The effect of the intact core and the open and in-filled fractures on the specific energy is studied, presenting the link between the fracture frequency and the specific energy. The main conclusions are as follows:

1. The variability of each drilling parameter, such as the penetration rate, drilling force, and penetration rate,
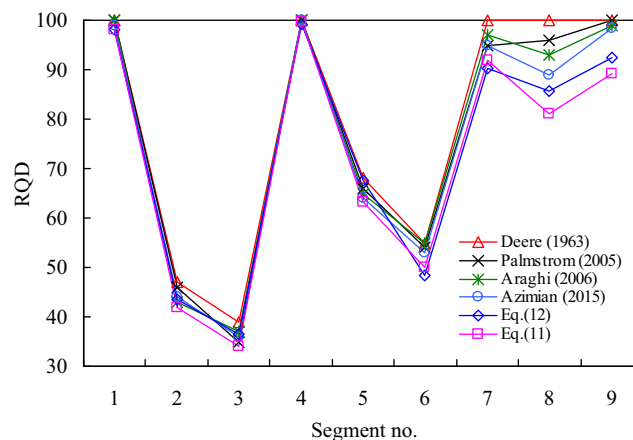
Fig. 14 Comparison of the proposed method in this paper with the previous methods

Table 1 The comparative study of the proposed method with the previous methods

No. segment	RQD (Deere 1963)	RQD$_1$ (Azimian 2015)	MRQD (Araghi 2006)	RQD (Palmstrom 2005)	Eq. (12)	Eq. (11)
1	100	99	100	100	98.2	98
2	47	44	43	46	43.6	42
3	39	36	37	35	36.5	34
4	100	100	100	100	99.3	99.7
5	68	64	65	66	67.5	63.3
6	55	53	55	54	48.5	50
7	100	95	97	95	90.4	92
8	100	89	93	96	85.7	81
9	100	98.5	99	100	92.5	89.3

provides a straightforward relation to the rock fracture and the fracture zone of a rock mass with and without being in-filled.

2. The standard deviation of 0.18 for the specific energy can be used as a critical point to distinguish between the segments of intact core and fracture.

3. The comparative study of the proposed method with the previous methods is carried out to demonstrate the reliability. The RQD value from the proposed method is mostly at or slightly smaller than the values from previous method and tends to be a conservative estimation.

List of symbols M, torque (N·m); w, rotation speed (rpd); F, drilling force (N); e, specific energy (N/mm^2); v, Penetration rate (mm/min); A, excavation area (mm^2); f, standard deviation of the specific energy; s_{min}, minimum value of the standard deviation; s_{max}, maximum value of the standard deviation; λ, Fracture frequency; N, fracture sets number; λ_i, fracture frequency normal to set i; θ_i, fracture orientation; t, selected threshold value; ζ, fitting parameter of relationship curve between the fracture frequency and the standard deviation of specific energy

Declarations

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