A new approach to evaluate rock drillability of polycrystalline diamond compact bits using scratch test data

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Abstract
Rock drillability is a comprehensive index that indicates the ease of drilling a hole in the rock mass, which is a main basis for the design of drilling bits, the optimization of drilling operational parameters, and the prediction of rate of penetration. This paper established a conversion relationship between mechanical specific energy measured from micro-drilling tests and mechanical specific energy measured from scratch tests, based on the consistency of rock breaking mechanism between these two types of tests. By incorporating the methodology of calculating rock drillability grade of polycrystalline diamond compact bits, a new mathematical model for predicting rock drillability of polycrystalline diamond compact bits is developed. Subsequently, a new method for acquiring continuous rock drillability profile by scratching the core surface is developed. A wide range of rocks with different hardness were tested by the proposed scratch method. The results show that the new model has high consistency with the results of laboratory micro-drilling tests. For example, the average errors of sandstone, shale, and carbonate test results are only 7.41%, 8.18%, and 4%, respectively. The new method can fully characterize the effect of mineral composition, cementation strength, and microstructure of rock on drillability. Besides, the new model has high utilization efficiency of expensive core samples because the core usually remains nondestructive after scratch tests.

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Keywords
Mechanical specific energy, scratch test, PDC bit, drillability

Introduction
Teale (1965) first proposed the concept of mechanical specific energy (MSE, also known as specific crushing energy) and used it to describe the performance of drilling bits. MSE is defined as the mechanical energy required to break rock of a unit volume (Anemangely et al., 2019). It is a parameter that reflects the combined influence of rock mechanical properties (e.g., strength and hardness) and drilling parameters (e.g., weight on bit (WOB) and rate of penetration (ROP)) on rock breaking. The theory of MSE has been widely used in monitoring and predicting drilling performance, designing new drilling techniques and tools, and evaluating the drillability of formation rocks (Alali et al., 2012; Amadi and Iyalla, 2012; Cherif and Bits, 2012; Koederitz and Johnson, 2011; Pei, 2012). This paper will focus on the evaluation of drillability which is a comprehensive index that indicates the ease of drilling a hole in the rock mass and serves as a main basis for drilling bit design, optimization of drilling operational parameters, and prediction of penetration rate of the bit (Anemangely et al., 2018).

Based on Teale’s theory of MSE, Detournay and Defourny (1992) developed a theoretical model for determining MSE using scratch test data and manifested that MSE of rock is approximately equal to its uniaxial compressive strength (UCS). Richard et al. (1998) further demonstrated that the friction coefficient of a scratch test is equal to the intrinsic friction coefficient of the tested rock. Schei et al. (2000) analyzed the force acting on a scratch cutter and found that there is a strong correlation between the hardness of rock and scratch measurements. Based on this finding, Schei et al. presented a preliminary model for rock hardness evaluation using scratch test results; however, the accuracy of the evaluation model is not very satisfactory. Chen et al. (2017a, 2017b) established an empirical model and a theoretical model for assessing rock drillability of polycrystalline diamond compact (PDC) bits using scratch tests. However, the theoretical basis of the models is relatively weak and they are only valid for soft to medium-hard rocks and will lose their accuracy with the increase of rock hardness. Moreover, some input parameters of their models are very difficult to determine, restricting the wide application of the models.

This paper analyzes the inter-relationship of rock breaking mechanism between micro-drilling tests and scratch tests and then, based on the inter-relationship, establishes the correlation of MSE obtained from these two types of tests. Furthermore, a new mathematical model for predicting rock drillability with PDC bits based on the results of scratch tests is developed. Compared with the model of Chen et al. (2017a, 2017b), the new model has a wider applicable range, valid for soft to very hard rocks. In addition, the model has less parameters, and thus, it is much easier to use.

Review of MSE models
Teale (1965) carried out a large number of fundamental experiments of MSE with different types of bits and rocks and proposed the first MSE model. Since then, a number of researchers have conducted scientific experiments and developed a couple of MSE models.
An elegant MSE model should possess the features of: (1) MSE should be approximately equal to UCS of the rock while drilling in different lithologic formations; (2) parameters of the model are easy to measure and calculate; and (3) the application scope of the model is wide - suitable for various types of rocks and drilling bits. Existing MSE models reported in the literature are summarized as follows.

a. Teale model (Teale, 1965)

\[
MSE = \frac{WOB}{A_b} + \frac{120\pi \cdot N \cdot T}{A_b \cdot ROP}
\]  

b. Dupriest and Koederitz model (Dupriest and Koederitz, 2005)

\[
MSE = 0.35 \left( \frac{WOB}{A_b} + \frac{120\pi \cdot N \cdot T}{A_b \cdot ROP} \right)
\]

c. Cherif and Bits model (Cherif and Bits, 2012)

\[
MSE = E_m \cdot \left( \frac{4WOB + 480N \cdot T}{\pi \cdot D_b^2 \cdot ROP} \right)
\]

d. Pessier and Fear model (Pessier and Fear, 1992)

\[
MSE = WOB \left( \frac{1}{D_b} + \frac{13.33 \cdot \mu \cdot N}{D_b \cdot ROP} \right)
\]

\[
\mu = 36 \left( \frac{T}{D_b \cdot WOB} \right)
\]

e. Fan model (Fan et al., 2012)

\[
MSE = WOB \cdot \left( \frac{1}{A_b} + \frac{2.91 \cdot N}{D_b \cdot ROP} \right)
\]

f. Detournay and Defourny model (Detournay and Defourny, 1992)

\[
MSE = \frac{F_s}{w \cdot d} = \frac{F_n}{\tan(\theta + \psi) \cdot w \cdot d}
\]

where MSE is the mechanical specific energy, MPa; WOB is weight on bit, kN; \( A_b \) is the area of drill bit, mm\(^2\); \( N \) is rotational speed, r/min; \( T \) is torque on drill bit, kN \( \cdot \) m; ROP is the rate of penetration, m/h; \( D_b \) is diameter of drill bit, mm; \( E_m \) is mechanical efficiency, dimensionless; \( \mu \) is sliding friction factor, dimensionless; \( F_s \) is tangential force acting on scratch
cutter, \( F_n \) is normal force acting on scratch cutter, \( N \); \( \theta \) is back rake angle of scratch cutter, \( ^\circ \); \( \psi \) is interfacial friction angle, \( ^\circ \); \( w \) is width of scratch cutter, mm; \( d \) is scratching depth, mm.

Teale model has the advantage of less parameters. In drilling practices and laboratory tests, WOB, rotational speed (\( N \)), and ROP can be directly measured in real time, while torque (\( T \)) cannot be measured directly. It is, therefore, often obtained through indirect calculations using other parameters. As a result, Teale model has certain inaccuracy in parameter determination and MSE prediction. The Dupriest and Koederitz model and Cherif and Bits model amended the coefficients in Teale model and introduced the parameter of mechanical efficiency (\( E_m \)). However, this parameter is influenced by a variety of factors such as drilling conditions, bit types, and well depth. It should not be a constant of 35% as commonly used. Pessier model combines mechanical efficiency and torque and further optimizes Teale model. As a result, the prediction accuracy is improved by a certain extent. However, sliding friction factor and torque cannot be directly measured, so it still has the shortage of parameter uncertainty. Fan model incorporates the relationship between torque, WOB, and bit diameter. The parameters of this model are very easy to measure and calculate. The Detournay and Defourny model is different from the above five models. It is developed based on the results of laboratory scratch tests, in which the rock surface is continuously scratched using a blade with a certain scratch speed and depth. The force acting on the blade is measured in real time during the test; and then, MSE of the rock sample can be easily calculated using the test data.

Based on the analysis of the MSE models, we can find that the torque of the bit cannot be measured directly, and thus a simple conversion of torque from other factors (e.g., WOB, rotational speed, and bit parameters) should be used as far as possible. Moreover, drillability of rock can be evaluated using scratch test data by establishing a relationship between drillability measured from micro-drilling test and MSE calculated based on Detournay and Defourny model using scratch test data.

**Drillability model**

Based on the theory of MSE, Chen et al. (2017a, 2017b) developed an empirical model and a theoretical model for evaluating rock drillability with PDC bits, which contribute a preliminary technique for acquiring continuous drillability profiles by scratching the surface of rocks.

The empirical model is expressed as

\[
K_{ds} = \log_2 \left[ \frac{(0.0119(MSE_s)^2 + 1.5454MSE_s - 136.43) \times V}{P} \right] \tag{8}
\]

where

\[
P = 2.61 \cdot WOB \cdot D_b \cdot N \cdot \phi \tag{9}
\]

The theoretical model is expressed as

\[
K_{ds} = \log_2 \left[ \frac{(a \cdot MSE_s + b) \cdot r}{\mu_s \cdot WOB} \right] + 0.7105 \tag{10}
\]
where $K_{ds}$ is the value of drillability, dimensionless; $MSE_s$ is the specific energy of the rock for scratch test, MPa; $V$ is the volume of crushed rock by the scratch of micro-PDC bit, mm$^3$; $P$ is the power required for the micro-PDC bit to crush the rock, W; $r$ is the radius of the bit, mm; $t$ is the drilling time, s; $\mu_s$ is the ratio of the tangential force to the normal force acting on the PDC bit, dimensionless; $\varnothing$ is an empirical coefficient, equal to 0.6 in this study; $a$ and $b$ are fitting coefficients.

The empirical model adopted the empirical formula of the power required to break rocks with PDC bits proposed by Ma and Wang (2006). The mechanical energy consumed to drill to an objective depth is obtained through multiplying power by drilling time. And then, $MSE$ in the micro-drilling test is calculated through dividing the mechanical energy by the volume of broken rock. Next, the relationship between the MSE of micro-drilling tests and the MSE of scratch tests is established. Finally, combined with the method for calculating drillability of PDC bit, the empirical model of rock drillability based on scratch test data is obtained. The empirical model has some issues on power conversion efficiency and thus possesses some errors. However, the following of this paper will focus mainly on the reconstruction and improvement of the theoretical model, rather than focusing on the empirical model.

The micro PDC bit rotates and cuts the rock under the action of WOB and torque. The theoretical model gives the formula to calculate the MSE of the bit in one circuit, expressed as

$$MSE_d = \frac{11 \mu_s \cdot WOB \cdot t}{18r}$$  \hspace{1cm} (11)

where $MSE_d$ is the MSE in micro-drilling test, MPa. In addition, the drillability of the rock can be expressed as a function of drilling time in micro-drilling test

$$K_{ds} = \log_2 t$$  \hspace{1cm} (12)

where $t$ is the drilling time.

Next, the conversion from MSE of scratch test to MSE of micro-drilling test is obtained through data fitting, expressed as

$$MSE_d = a \cdot MSE_s + b$$  \hspace{1cm} (13)

Finally, a mathematical model (equation (10)) for evaluating rock drillability with PDC bit using scratch test data is established by combining equations (11) to (13). However, this theoretical model has some limitations.

First, it is applicable only to soft (Type I) formations to medium-hard (Type II) formations, but not applicable to relatively hard (Type III) formations. The model calculates MSE of the micro PDC bit in one circuit; thus, the harder the formation, the fewer drilling footage per circle and the worse adaptability of the model. Second, parameter $\mu_s$ is difficult to determine. $\mu_s$ is the ratio of the tangential force to the normal force acting on the PDC bit. It varies strongly with region, stratum, and lithology. As a result, statistical methods are usually required to determine this parameter, and thus, a large number of micro-drilling tests are needed, which are time-consuming and cost a great deal of precious cores. In view
of these problems, we conducted further research in this paper to reconstruct the theoretical model and to improve its reliability and applicability.

**Laboratory tests**

*Micro-drilling test*

In order to study the rock drillability of PDC bits using scratch tests, we have to know the drillability of rock first. Then, based on the theory of MSE, we linked the results of micro-drilling tests and scratch tests to determine rock drillability using scratch test data. In this work, we used micro-PDC bits and micro-drilling tests recommended in standard “SY/T 5426—2000-Rock Drillability Measurement and Its Classification” to measure the drillability of rock. Micro-drilling tests are conducted using the automatic drillability test system manufactured by Shiyi Technology Company of China University of Petroleum (see Figure 1). The system consists of a rock sample holder, a micro drill bit, a load unit, a power transmission unit, a drilling depth measurement device, and an automatic data acquisition system. The micro PDC bit consists of a steel body and two PDC cutters. The micro bit has an outer diameter of 32 mm. The PDC cutters have a diameter of 13.3 mm and a back rake angle of 20° (see Figure 2).

The core samples are drilled perpendicularly to their cross sections with a WOB of 500 N and a revolution speed of 55 r/min. A hole with a depth of 4 mm is drilled in each micro-drilling test. The first 1 mm of each hole is a predrilled depth, and test data (e.g., drilling time) are only recorded for the next 3 mm of the hole. For each test, at least three holes are drilled, and the results are averaged as the result of the test. The drillability of the rock can then be calculated using equation (12). Drillability can be classified into three grades, as shown in Table 1. It should be noted that the vibration of drill strings may also affect drilling efficiency (Wang et al., 2017) and thus drillability of the formation in real drilling practices; however, drill-string vibration is not simulated in the micro-drilling tests and its effect on drillability is beyond the scope of this study. It should also be noted that although

![Figure 1. Micro-drilling system for rock drillability measurement.](image-url)
we measured the drillability of rock using micro-drilling test with PDC bit in this work, the focus of this paper is to evaluate the drillability of rock, rather than investigating the performance of PDC bits.

**Scratch test**

Scratch tests are conducted using the Mechanical Profiler Test System of TerralTek (see Figure 3). The system consists of a drive unit, a load measurement device, a displacement measurement device, a scratch cutter, and an automatic data acquisition system. During the test, the scratch cutter scratches the surface of the rock with a constant depth and velocity (see Figures 4 and 5). In this study, the rock samples are scratched by a 5 mm wide cutter.

![Schematic of micro PDC drill bit. PDC: polycrystalline diamond compact.](image)

**Figure 2.** Schematic of micro PDC drill bit. PDC: polycrystalline diamond compact.

| Table 1. Rock drillability grades. |
|-----------------------------------|
| **Class**                        | **Grade** | **Drillability (K_d)** | **Drilling time (s)** |
| Type I (soft rock)               | (1)       | <2                     | <2^2                  |
| (2)                              |           | 2–<3                   | 2^2–<2^3              |
| (3)                              |           | 3–<4                   | 2^3–<2^4              |
| (4)                              |           | 4–<5                   | 2^4–<2^5              |
| Type II (medium-hard rock)       | (5)       | 5–<6                   | 2^5–<2^6              |
| (6)                              |           | 6–<7                   | 2^6–<2^7              |
| (7)                              |           | 7–<8                   | 2^7–<2^8              |
| Type III (hard rock)             | (8)       | 8–<9                   | 2^8–<2^9              |
| (9)                              |           | 9–<10                  | 2^9–<2^10             |
| (10)                             |           | ≥10                    | ≥2^10                 |
Figure 3. Mechanical Profiler Test System used for scratch tests in this study.

Figure 4. Schematic of the scratch assembly for scratch tests: 1, cutter; 2, chuck; 3, nut; 4, mounting hole; 5, tool rest.

Figure 5. Scratch test on a full-size core.
with a scratch depth of 0.18 mm and a scratch velocity of 3 mm/s. Meanwhile, the force acting on the cutter and the displacement of the cutter are monitored and recorded, so the strength parameter profile of rock can be obtained in real time (Detournay and Defourny, 1992). Three or more repeated tests are conducted, and the average value is taken as the final experimental result. The key parameters of the experiment are shown in Table 2. The velocity and depth of scratching are selected according to the strength of rocks to ensure that the scratched rocks fail in a plastic mode.

### Evaluating drillability of PDC bit using scratch test data

**Rock breaking mechanism of micro-drilling test and scratch test**

Both micro-drilling test and scratch test break rock by cutting the rock with PDC blade. In micro-drilling tests the micro PDC bit rotates and cuts the rock under the action of WOB and torque, while in a scratch test the cutter scratches the rock surface with axial load and horizontal driving force. Numerous experimental investigations have demonstrated that there are two principal rock failure modes under cutting/scratching—a ductile failure mode and a brittle failure mode. When the cutting depth is less than a threshold depth, the rock fails in a ductile mode; otherwise, it fails in a brittle model (see Figure 6). Under ductile failure mode, the cuttings are fine and uniform and generated in a continuous manner, and the cutting force is proportional to the energy consumed (Adachi et al., 1996; Almenara, 1992; Detournay and Defourny, 1992; Ghoshouni and Richard, 2008; Pei, 2012; Richard, 1999; Richard et al., 1998; Schei et al., 2000). MSE is closely related to inherent mechanical strength and drillability of rocks. This provides the basis for

| Scratch width (mm) | Scratch depth (mm) | Scratch velocity (mm/s) |
|-------------------|--------------------|------------------------|
| 5 or 10           | 0.1–0.3            | 2.0–5.0                |

**Figure 6.** Failure modes while cutting a rock (Richard, 1999): (a) plastic failure mode and (b) brittle failure mode.
correcting the results of micro-drilling tests and scratch tests. To summarize, under the condition of ductile cutting, MSE can be used to link scratch test data with micro drillability test data, implying that drillability of PDC bits can be evaluated with scratch tests.

**MSE of micro-drilling tests**

The PDC bit rotates and cuts the rock under WOB and torque. The surface of the PDC cutter has a constant inclination angle $\alpha$ with respect to the vertical direction, and the total force acting on the cutter can be decomposed to two components—a tangential force $F_s$ along the cut direction and a normal force $F_n$ along the vertical direction (see Figure 7). The WOB is 500 N in all micro-drilling tests, but the torque cannot be measured directly as aforementioned. Therefore, we choose Fan’s MSE model in the Review of MSE Models section which simplifies torque conversion to calculate MSE of micro-drilling tests. Given measured time $t$ to dill a 3 mm hole in the tests, Fan’s MSE model can be expressed as

$$MSE = WOB \cdot \left( \frac{1}{A_b} + \frac{0.97 \cdot N \cdot t}{D_b} \right)$$

(14)

**MSE of scratch tests**

Richard (1999) and Richard et al. (1998) analyzed the stress acting on a cutter under plastic cutting mode in scratch tests. The normal of cutter face keeps at a constant angle $\theta$ with respect to the horizontal cutting direction. Ignoring the frictional force at the bottom of the cutter, the total force $F$ acting on the cutter can be decomposed to two components—a tangential force $F_s$ along the direction of scratch and a normal force $F_n$ perpendicular to the scratch surface, as shown in Figure 8. The MSE of scratch test can be determined using equation (6). Continuous MSE profiles of a core sample can be obtained directly from scratch tests. As mentioned earlier, Detournay and Defourny (1992) have demonstrated that the value of MSE in plastic cutting mode is equal to the UCS of the rock.

![Figure 7. Schematic of the force acting on a cutter of a PDC bit in micro-drilling test. PDC: polycrystalline diamond compact.](image)

Determining rock drillability of PDC bit using scratch test data

Now we have selected the models to calculate MSE for micro-drilling test and scratch test as described in earlier subsections. Next, we will conduct a large number of experimental tests on different rock samples and use the test data to establish a relationship between MSE of the two types of tests. Finally, based on the inter-relationship of the two tests, a rock drillability evaluation model using scratch test data is developed. In this section, we describe the method of evaluating drillability of PDC bits using scratch tests.

(1) Test results

Due to the complex compositions and structures of rocks, drillability and strength of different rocks can vary significantly. In order to ensure the comprehensiveness and representativeness of the experimental data, a total number of 43 full-scale core samples with four different lithology are tested. These samples include sandstone samples from an oilfield in northeast China, shale samples from an oilfield in southwest China, igneous rock samples from an oilfield in northwest China, and carbonate rock samples from an oilfield in northwest China (see online Appendix 1).

Selection of corresponding micro-drilling test data and scratch test data is very important for building a relationship between them. For example, for the sandstone core sample (B202-7) shown in Figure 9 with homogeneous lithology, the correspondence between the two test results is relatively good. In other words, MSE measured from micro-drilling test and scratch test at different locations does not have strong fluctuation. However, for core samples of strong heterogeneity, if the two tests data are not from the same measurement location, there can be a significant deviation. For example, Figure 10 shows a shale core sample (W1-3) with MSE fluctuating sharply between 50 and 220 MPa with the change of mineral compositions and microstructures along the axial direction of the core. Therefore, in order to ensure good correspondence between data sets of the two types of tests, it is necessary to select micro-drilling test locations according to the MSE profiles of scratch tests. Figure 11 shows cores B202-7 and W1-3 after micro-drilling tests.

A total of 143 sets of micro-drilling test data and scratch test data are obtained for sandstone, shale, igneous and carbonate rocks, as reported in online Appendix 1. Substituting the
Figure 9. MSE profile of scratch test and micro-drilling test location of sandstone core sample B202-7. MSE: mechanical specific energy.

Figure 10. MSE profile of scratch test and micro-drilling test location of shale core sample W1-3. MSE: mechanical specific energy.

Figure 11. Core sample of (a) B202-7 and (b) W1-3 after micro-drilling tests.
drill time of micro-drilling tests into equations (12) and (14), the drillability and MSE of PDC bits can be obtained, respectively. MSE of scratch test can be calculated directly with the Detournay and Defourny model using scratch test data as introduced in the Review of MSE Models section. The relationship between the MSE of micro-drilling tests \( \text{MSE}_d \) and the MSE of scratch tests \( \text{MSE}_s \) is given by Equation (15) and shown in Figure 12.

\[
\text{MSE}_d = 0.0029 \cdot \text{MSE}_s^2 \cdot 4106
\] (15)

(2) Drillability model based on scratch test data

Combining equations (12) to (15), an evaluation model of rock drillability of PDC bit using scratch test data can be obtained

\[
K_{ds} = \log_2 \left( \frac{0.0029 \cdot \text{MSE}_s^2 \cdot 4106 \cdot D_b}{WOB \cdot N} - \frac{1.03 \cdot D_b}{A_b \cdot N} \right)
\] (16)

Drillability calculated with this equation for each test is also reported in online Appendix 1.

(3) Error analysis

Errors of the drillability evaluation model (equation (16)) based on scratch test data are also analyzed, and the results are reported in online Appendix 1. Table 3 presents a set of representative cases with errors that are caused by three main reasons.

The first type of error is caused by low strength and drillability of the core. For example, core W1-4 in Table 3 has a low average drillability of 1.30 measured directly from micro-drilling tests and a drillability of 1.59 predicted with the drillability model (equation (16)) using scratch test data. Thus, the average relative error of the prediction is 22.9%. However,
the difference between the drillability of 1.59 from the scratch test and the average drillability of 1.30 from the micro-drilling test is 0.29, which is considered to be acceptable for practical applications. The drillability of 1.30 and 1.59 indicates that the rock is Type I rock (soft rock) according to the drillability grade classification listed in Table 1. However, if the drillability results from above two types of test can be Type 1 and 2 simultaneously, there might be a significant error and need to re-examine the apparatus and re-test.

The second type of error is induced by core breakage during micro-drilling tests. For example, the maximum error of shale core Y1-4 in Table 3 is as high as 49.62%. A close observation of this core shows that it is hard and brittle with extensively developed micro-cracks. During micro-drilling tests, the core was broken; rock fragments spalled off around the drill hole as shown in Figure 13(b). This core failure causes increase or decrease in drilling time, and thus increasing the error. Moreover, reduction of core strength due to breakage also increases the error. The average drillability of core Y1-4 is 1.76 and 1.65 from micro-drilling tests and scratch tests, respectively. Once again, although the relatively error 49.62% is very high, the absolute error is only 0.12 which is acceptable from a practical point of view.

The third type of error is resulted from lithology variation in the core. For example, shale core Y1-5 has sudden lithology change due to local pyrite development as shown in Figure 13(c), resulting in different drilling time at different micro-drilling locations. The drilling time in pyrite-development area is only 3.92 s, while drilling times at the other two locations without pyrite development are 44.54 s and 24.23 s, respectively. However, the variation of drilling time caused by lithology change is real and acceptable.

Figure 14 is a statistical analysis of the errors of all 143 sets of drillability data predicted based on equation (16). It is found that 59 sets have an error less than 5%, 39 sets have an error between 5% and 10%, and 23 sets have an error between 10% and 15%. The percentage of data sets with an error less than 15% reaches 83.45%. The statistical analysis indicates that the drillability prediction model of equation (16) has high precision and good adaptability in either soft or hard formations.

(4) Comparison with the model of Chen et al. (2017a)

Using the 47 sets of micro-drilling and scratch test data reported in Chen et al. (2017a), we calculated rock drillability using the current model and the model of Chen et al. (2017a). It should be noted that all the tests of Chen et al. (2017a) are on soft to medium-hard rock
A comparison of the prediction results of the two models in Figure 15 shows that the two models agree very well with each other. A further check by comparing the predicted drillability with measured drillability by micro-drilling tests shows that the average errors of the current model and the model of Chen et al.

Figure 13. Cores Y1-4 and Y1-5 before and after micro-drilling tests: (a) core Y1-4 before micro-drilling test, (b) core Y1-4 after micro-drilling test, (c) core Y1-5 before micro-drilling test, and (d) core Y1-5 after micro-drilling test.

Figure 14. Statistical analysis of drillability prediction error of equation (16).
are 5.93% and 6.01%, respectively. The small errors indicate that both models work well for soft to medium-hard rock.

As aforementioned, the new model works better for hard rock compared with the model of Chen et al. (2017a). To illustrate this point, we selected six groups of tests data (summarized in Table 5) from Appendix 1 with measured drillability over 8.0 (hard rock as defined in Table 1) and predicted the drillability using the two models. The prediction errors of each set are shown in Figure 16. The results clearly show that the new model has much smaller errors compared with Chen et al. (2017a), confirming its better applicability for hard rock.

**Case studies**

The drillability model of PDC bit using scratch test data has been used in evaluating the drillability of Longmaxi formation in southwest China and Yanchang formation in north China.
Figure 17. MSE and drillability profiles of a relatively homogeneous shale core from Well J10 in southwest China. MSE: mechanical specific energy.

Figure 18. MSE and drillability profiles of a relatively homogeneous sandstone core from Well W14 in north China. MSE: mechanical specific energy.

Figure 17 shows the drillability profile of a relatively homogeneous shale core of Longmaxi formation from Well J10. The drillability predicted using scratch test data along the core is quite uniform and around 2.60, and the average drillability from micro-drilling tests is 2.81, indicating a small error of 6.16%.

Figure 18 shows the continuous drillability profile of a sandstone core from Yanchang formation in Well W14, north China. The drillability predicted from scratch test data evenly distributed around 4.20, and the average drillability from micro-drilling tests is 4.36, indicating a small error of 2.52%.

Figure 19 shows that the continuous drillability profile of a carbonate core from Linxiang formation in Well D14, southwest China. It can be seen that MSE along the core fluctuates...
dramatically between 100 and 350 MPa and drillability fluctuates between 2.0 and 7.0. These fluctuations reflect the influence of local variations of mineral composition, cementation strength, and microstructure of the rock. In this case, the traditional micro-drilling tests at a few scattered points cannot fully represent the drillability of the entire core section, while scratch tests are superior.

Table 4 compares rock drillability of PDC bits determined with scratch test data \( k_{ds} \) and measured directly with micro-drilling test \( k_d \). The error of the method using scratch test data is

\[
\text{error} = \frac{\text{true value} - \text{estimated value}}{\text{true value}} \times 100 \%
\]

Table 5 compares rock drillability of PDC bits determined with scratch test data \( k_{ds} \) and measured directly with micro-drilling test \( k_d \). The error of the method using scratch test data is

\[
\text{error} = \frac{\text{true value} - \text{estimated value}}{\text{true value}} \times 100 \%
\]

Table 4. Drillability prediction for formations in southwest and north China.

| Region              | Well No. | Formation/Lithology          | \( k_d \) | \( k_{ds} \) | Error (%) |
|---------------------|----------|------------------------------|-----------|-------------|-----------|
| Southwest, China    | J10      | Longmaxi formation/shale     | 2.81      | 2.64        | 6.16      |
|                     | D4       | Linxiang formation/carbonate| 6.62      | 6.38        | 3.63      |
| Northeast, China    | W14      | Yanchang formation/sandstone| 4.36      | 4.25        | 2.52      |

Table 5. Test data sets used for the comparison of the current model and the model of Chen et al. (2017a).

| Test data set no. | Core no. | Lithology | Micro-drilling time (s) | Drillability of micro-drilling test | MSE of micro-drilling test (MPa) | MSE of scratch test (MPa) |
|-------------------|----------|-----------|-------------------------|------------------------------------|----------------------------------|--------------------------|
| 1                 | M3       | Carbonate | 521.42                  | 9.03                               | 7243.15                          | 398.61                   |
| 2                 | M3       | Carbonate | 318.17                  | 8.31                               | 4420.00                          | 383.02                   |
| 3                 | YB1      | Igneous   | 329.20                  | 8.36                               | 4573.21                          | 362.92                   |
| 4                 | YB1      | Igneous   | 342.05                  | 8.42                               | 4751.70                          | 356.67                   |
| 5                 | YB1      | Igneous   | 312.19                  | 8.29                               | 4336.94                          | 351.12                   |
| 6                 | J41-3    | Sandstone | 319.59                  | 8.32                               | 4439.73                          | 375.74                   |

MSE: mechanical specific energy.
data is between 2.52% and 6.16%. The relatively small error once again demonstrated that the drillability prediction method proposed in paper based on scratch tests can be applied in different areas with different lithology.

Conclusions and recommendations

A mathematical model for evaluating rock drillability of PDC bits using scratch test data is developed in this paper. Applications of the model to a variety of rocks with different hardness show that it has high consistency with drillability measured directly from laboratory micro-drilling tests. The new method based on scratch tests has the advantages of providing continuous drillability profile along the scratch path and characterizing the influence of mineral composition, cementation strength, and micro structures of rock on drillability, superior to the traditionally used micro-drilling test method which can only measure drillability at scattered points.

Further steps of this study should be extended to laboratory tests under multiple factors (e.g., temperatures, confining pressure, and pore pressure) and develop drillability evaluation models considering the coupling between these factors. Such drillability models would be of great importance for designing and selecting drill bits and improving the efficiency of deep and ultra-deep drilling.

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Supplemental Material

Supplemental material is available for this article online.

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Appendix

Notation

\( a \) and \( b \) fitting coefficients
\( A_d \) area of drill bit
\( d \) scratching depth
\( D_d \) diameter of drill bit
\( E_m \) mechanical efficiency
\( F_n \) normal force acting on scratch cutter
\( F_s \) tangential force acting on scratch cutter
\( K_{ds} \) value of drillability
\( MSE_d \) mechanical specific energy of micro-drilling test
\( MSE_s \) mechanical specific energy of scratch test
\( N \) rotational speed of drill bit
\( P \) power required for micro-PDC bit to crush rock
\( r \) radius of drill bit
\( t \) drilling time
\( T \) torque on drill bit
\( V \) volume of crushed rock
\( w \) width of scratch cutter
\( \theta \) back rake angle of scratch cutter
\( \mu \) sliding friction factor
\( \mu_q \) ratio of tangential force to normal force acting on PDC bit
\( \phi \) empirical coefficient
\( \psi \) interfacial friction angle