Evaluation methods and standards for rock drillability in oil and gas drilling engineering in China: A review

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Abstract: In western China, 70% of the oil, gas, and geothermal resources are buried in deep formations (more than 3000 m), but the low rate of penetration has become a key factor restricting the development of these resources. Rock drillability evaluation is a basic task for oil, gas, and geothermal drilling engineering design that includes bit design, bit selection, and drilling parameter optimization. Different tests and standards to evaluate rock drillability have been developed worldwide. Against this backdrop, the evaluation methods and standards for rock drillability are reviewed. Various rock drillability tests and classification standards are compared and analyzed. Results show that these methods and standards are inaccurate and fail to meet the design requirements of drilling technology and bit selection in deep and ultradeep drilling wells. In China, micro-drilling test is commonly used to evaluate rock drillability in oil and gas drilling engineering. This method was developed as an oil and gas industry standard and has been used for more than 40 years. However, its results do not reflect the significant effects of high temperature and pressure at the bottom hole on rock drillability and breaking; thus, the results cannot be used in drilling designs. Testing methods and classification standards for rock drillability require innovative developments. This review highlights the following: (1) the classification standards for rock drillability must be refined in the future to meet the requirements of drilling designs in deep and ultradeep wells; (2) efficient and fast rock drillability tests are required to deal with complex and difficult formations; (3) the influence of the real physical environment of the borehole bottom on rock drillability must be further clarified.

1 Introduction
Our world is rich in deep and ultra-deep oil and gas resources. Up to 70% of the oil and gas resources of western China are buried in deep formations (below 4500 m). However, the high temperature and stress of deep and ultra-deep wells cause many technical difficulties [1]. Moreover, low drilling efficiency is an important technical bottleneck that restricts deep oil and gas development. Rock drillability is a significant indicator of rock-breaking difficulty. The evaluation of rock drillability is crucial for drilling engineering design, such as in drill-bit optimization and design and in speed-up-process parameter optimization.

Rock classification research, from the perspective of drilling engineering, has a long history and is generally divided into two schools. Some scholars [2] advocated classifying the rock’s physical and mechanical properties, whereas others advocated classifying its “drillability” with a real drill. In 1977,
to unify rock classification, the International Association of Rock Mechanics (ISRM) classified rocks according to their uniaxial compressive strength. Subsequently, the rocks were divided into extremely soft, soft, medium hard, hard, and extremely hard. Several revisions were later made to this classification.

To meet drilling engineering requirements, multiple studies in China focused on rock drillability classification beginning in the 1960s. Given the research achievements at home and abroad, hardness and micro-drilling tests were selected as the main evaluation methods. On the basis of a large number of experiments and data analyses, rock drillability was divided into 10 grades [3, 4]. Then, the SY/T 5426-2000 rock-drillability measurement and classification method was established. It was revised in 2016 to form SY/T 5426-2016, “to determine oil and gas drilling engineering rock drillability and classification.” This method has become an important basis for guiding oil and gas drilling engineering design, bit selection design, and drilling practice. As drilling technology has progressed, rock drillability has been widely adopted as the industry classification standard; however, it does not meet the development needs of the drilling industry. The reasons for which are as follows.

First, drilling engineers generally report that drilling design parameters cannot be determined using the current drillability grading standards, and the appropriate bit cannot be selected according to the drillability level. Drilling technology has developed greatly with respect to soft to medium-hard strata, in which it can meet the demands of acceleration. However, in hard to very hard rock formations, the drilling design and type selection are far from meeting the acceleration requirements.

Second, obtaining the core is difficult and expensive. Thus, most wells can only conduct core drilling at key strata. As destructive procedures, rock mechanics and drillability tests are expensive. Furthermore, drillability tests can only be conducted at key strata; hence, the drillability data of the entire well, from the wellhead to the reservoir, cannot be accurately obtained.

Third, many scholars expect to use the physical and mechanical properties of rocks to characterize their drillability. Many studies [5] have found clear indications of a significant correlation between a rock’s physical and mechanical properties and its drillability; however, these physical and mechanical properties cannot fully express the rock’s drillability characteristics [6].

Fourth, in actual deep drilling processes, the drill bit usually breaks the rock in a high-temperature and high-pressure environment. The mechanism by which the above factors affect rock drillability is unclear, and current drillability evaluation methods cannot confirm the influence of high temperature and stress on rock breaking.

The above analysis suggests that the current rock drillability classification standard is rough and imprecise. It cannot meet the need of deep and ultra-deep-well rock-breaking tool optimization and design under a complicated formation environment. In addition, the mechanism by which high temperature and pressure in deep strata affect rock drillability is complicated, and the regularity is unclear. Therefore, drilling tools cannot be designed and optimized according to the rock drillability characteristics at the actual bottom of the wellbore, restricting the innovative research and development of drilling technology and affecting the efficiency of deep-formation oil and gas development.

On the basis of the above problems and in view of the urgent demand for a refined theory and classification system for evaluating the rock drillability to increase deep-well drilling speeds, this article presents a deeper and more basic theory and interdisciplinary research method. This study aims to investigate the microstructural characteristics of rocks and develop a quantitative-description method and a mesoscopic structure-model characterization. Moreover, it aims to conduct a rock drillability experiment that simulates a high-temperature and high-pressure environment based on different mesoscopic rock structures and elucidate how the mesoscopic structure at the bottom of the wellbore influences rock breaking and drillability. Subsequently, it presents a new method and classification system based on the rock mesoscopic structural characteristics as a drillability evaluation theory. This study is expected to considerably promote drilling engineering technology innovation and enrich rock mechanics theories under the “high-temperature and high-stress environment of deep formations.”
2 Drillability Definition and application

In 1927, the American scholar Tillson [7] first proposed the concept of rock drillability—the difficulty of drilling a hole in rock, which demonstrates the comprehensive properties of rocks. Chinese and foreign scholars have a long history of researching on rock drillability tests and classification systems. The following four methods are commonly used to determine rock drillability grades: micro-drilling test, NTNU/SINTEF drillability test, mechanical specific energy method hardness index grading, and uniaxial compressive strength grading.

2.1 Micro-drilling test

The drillability test and classification method generally accepted in the petroleum engineering sector of China and other countries is the micro-drilling test. In 1950, Head [8] first used a micro-drill bit to drill in rocks at a weight on bit (WOB) of 417 lbs and a rotational speed of 110 rpm. The time to drill to a depth of 1/16 inch was used as the basis for drillability grading. This methodology divides rocks into 15 levels, providing a reliable theoretical basis for optimizing drill bit selection. In 1962, Rollow [9] proposed a method to predict drillability by using a micro-cone bit drill in the rock. A 1 1/4-inch micro-drill bit at a rotational speed of 55 rpm and a WOB of 200 lbs was used to perform the drillability test on the core until the drilling depth reached 3/32 inch. The drillability index was calculated according to the drilling speed, and the degree of wear on the micro-cone bit teeth was evaluated.

In 1982, Yin [4] investigated the drillability of different rock types; mudstone accounted for 30.6% of the samples, sandstone accounted for 47.8%, limestone accounted for 14.2%, and the rest accounted for 7.4%. All of these samples cored from the well with a depth ranging from 311 m to 4635 m. The drilling parameters of 100 lb WOB, 60 rpm rotational speed, and 2.4 mm drilling depth for testing drillability were adopted, and the time to conduct the test was recorded. The following formula was used for calculation $K_d = \log_d t$, where $K_d$ is the drillability index and $t$ is the time to drill 2.4 mm depth. The rock drillability was divided into 10 grades by analyzing a significant amount of test data, and the grading index was employed to guide the drill bit selection efficiently.

In 1992, based on the rock drillability evaluation technique recommended by Yin [4] and the Rollow [9] evaluation method, the first edition of the SY 5426-1991 [10] industry standard for rock drillability determination in China was promulgated. In 1993, Zou and Yin [11] proposed and implemented a method of polycrystalline diamond composite (PDC) micro-drill bit drillability test. This method was added to the micro-drill drillability evaluation system because a significant amount of PDC bits is being used in petroleum engineering. In 2000, China’s second edition of the industry standard for rock-drillability determination SY/T 5426-2000 [12] was promulgated. In June 2016, SY/T 5426-2016 [29], the new standard for the determination and classification of the rock drillability of oil-and-gas drilling projects, was promulgated. The new standard addressed the problem in which extremely hard rocks could not be tested in accordance with the old standard by increasing the WOB in the test. Then, a revised model was proposed, as shown in Table 1. Mao [13] evaluated the effect of wellbore pressure on drillability through laboratory micro-drilling test. Meanwhile, Li [14] tested field cores in the laboratory and then established a model to calculate the parameters of rock drilling resistance through regression analysis. A five-parameter radar map of formation drilling resistance was plotted using normalization processing on the basis of the relationships of interval transit time vs. rock hardness, internal friction angle, uniaxial compressive strength, abrasiveness grade, and rock drillability grade. This five-parameter radar map can be used in field petroleum engineering.

Table 1. Rock drillability classification [29]

| Category | Grade | $K_d$ | Cone bit | Drilling time (s) |
|----------|-------|-------|----------|------------------|
| Soft (I) | One   | < 2   | < 2<sup>2</sup> | Level 1 WOB: 22 - < 23, Level 2 WOB: 22 - < 23, Level 3 WOB: < 22 |
|         | Two   | 2 - < 3 | 22 - < 23 |

Note: The table provides a simplified explanation of the drillability classification system. The values represent specific conditions and ranges for testing and grading, demonstrating the complexity and consideration in determining drillability.
In addition to the abovementioned micro-drilling methods commonly used to test drillability, another set of micro-drill drillability tests was formed in Norway in the 1980s. In specific, the NTNU/SINTEF [15] drillability test was used to guide tool life prediction, drilling speed prediction, cost of mining, tunnel excavation, and underground engineering, as shown in Figure 1. Adopting the 1/10 drilling depth of 200 rotations by employing a 8.5 mm tungsten carbide micro bit at 88 lb WOB drilling in rock as the SJ, which is the parameter used to evaluate the rock’s resistance to drilling (Figure 1(a)). The method shown in Figure 1(b) was used to evaluate the rock’s brittleness index. The SJ value and the brittleness index were obtained by the above two tests to characterize comprehensively the drillability parameters of rocks, as shown in Figure 2. The rocks are divided into seven grades by using an index developed by Dahl [15]. Many Chinese and foreign scholars have accepted this evaluation method for mining, tunneling, underground engineering, and so on, but it has yet to be applied in petroleum engineering.

2.2 NTNU/SINTEF drillability test

![Figure 1. NTNU/SINTEF drillability test [15]](image-url)

(a). Sievers’ J-value test  
(b). Brittness index test
2.3 Mechanical specific energy method
A series of experiments with different bits and different rocks about drillability was carried out by T. Teale [16]. The concept of mechanical specific energy was introduced, and the original model of mechanical specific energy was obtained. In addition to the mechanical ratio, which can be used to evaluate the efficiency of the drill bit, it also provides a way to evaluate performance, such as drilling efficiency. Therefore, the study of mechanical specific energy is crucial to improve drilling efficiency, adjust drilling parameters according to actual working conditions, and monitor downhole working conditions while drilling. Pessier [17], Miguel [18], Hammoutene [19], and Dpriest [20] et al. modified the model of T. Teale to describe better the actual performance of the drill bit. To evaluate the working efficiency of the bit, Fan [21] calculated the mechanical specific energy by using the field data, thereby providing a theoretical basis for bit selection. In 1996, Xu [22] obtained the calculation formula of specific energy through a laboratory rock-breaking experiment and evaluated the working condition of drill bit in the bottom wellbore according to this formula. Wang [23] explained that using the specific energy method to select regional bit is helpful for the correct use of bit and can meet the needs of field drilling. Han [24] established a conversion relationship between mechanical specific energy measured from micro-drilling tests and mechanical specific energy measured from scratch tests and then developed a new mathematical model for predicting rock drillability. The model has high consistency with the results of laboratory micro-drilling tests.

2.4 Hardness index grading
The hardness of a material is often used to characterize its ability to resist the indentation of a hard object on its surface. This parameter is commonly used for drill bit selection and engineering design. Indentation hardness is generally used for petroleum engineering, although many testing methods can be used for hardness. As early as 1962, Soviet scholar Slinev [3] compared the rocks encountered in oil drilling on the basis of their hardness and plasticity coefficient. The rocks were divided into 15 grades of three categories by the hardness index and six grades of three categories by the plasticity coefficient index.

An experimental study on the hardness and drillability of 940 rock samples found a good nonlinear relationship between hardness and drillability. However, no apparent correlation was found between plasticity and drillability. Therefore, Zhan [3] created a drillability classification table according to experimental hardness and drillability results. In this table, drillability is directly graded with the rate
of penetration under the same WOB and rotational speed experimental parameters, as shown in Table 2.

Table 2. Rock drillability grade classification [3]

| Rock category | Soft (I) | Medium (II) | Hard (III) |
|---------------|----------|-------------|------------|
| Rock grade    | One      | Two         | Three      | Four        | Five        | Six         | Seven       | Eight       | Nine        | Ten         |
| Rock drillability (m/h) | 2.0–    | 1.0–        | 0.5–       | 0.3–        | 0.1–       | 0.06–      | 0.03–       | 0.01–       | 0.008–     | 0.004–     |
| Rock hardness (MPa)       | <100    | 100–        | 200–       | 500–        | 700–       | 1500–      | 2100–       | 2500–       | 3400–      | 3500–      |

2.5 Uniaxial compressive strength grading

In addition to using micro-drilling methods to test rock drillability and classify rocks, domestic and abroad scholars have proposed a method to classify rocks by grading their uniaxial compressive strength. In 1979, the ISRM divided rocks into seven levels according to their uniaxial compressive strength [25], as shown in Figure 3. This method is usually used in international petroleum engineering to guide the selection and engineering design of drill bits owing to the universal adaptability of the uniaxial compressive strength [26]; however, a unified classification standard has not been formed. Most drill bit companies use the bit and drilling parameters of their own classification systems that do not refer to the ISRM standard for classification. This lack of clear boundary in rock strength classification confuses engineers when selecting drill bits and drilling parameters [27]. Farhana [28] established a relationship between the drillability and UCS of granite samples.

Figure 3. ISRM rock-strength grading criteria[25]

The following problems of the standard drillability measurement and grading methods for the oil and gas industry have not been addressed despite numerous revisions. First, the samples tested by the standard do not cover all rock types. Yin [4] mainly tested rock samples from several fields in 1982, where mudstone accounted for 30.6% of the sample, sandstone for 47.6%, limestone for 14.2%, and other rocks accounted for 7.4%, however, hard rock types, such as granite, basalt, and other lithologies, were not involved. In 1993, Zou and Yin [11] investigated micro PDC bit drilling and found that slipping occurred when the standard PDC drillability test was applied. This result can be attributed to the fact that the rock is too hard to undergo the PDC drillability test, which has a limit point of 7.3, further illustrating that the current method does not cover all rock types. The 2016 version of the drillability test adjusted the testing standard that modified the WOB in terms of the above problem, but the drillability testing conditions (WOB, rotational speed) were modified. As a result, the test could not objectively reflect the mechanical properties of the rock.

Second, the drillability-classification standard is imprecise, causing large engineering errors in drilling engineering design and practice. The drilling time at the same drilling depth is recorded and then substituted to calculate drillability. The drilling time is doubled between each additional level according to the formula. Drillability levels 8, 9, and 10 are classified into one category; thus, engineers often believe that these levels can be grouped into one class for engineering design. However, the actual difference is significant.

Third, the current drillability test does not consider the influence of high-temperature and high-pressure environment at the bottom of the wellbore; thus, it cannot reflect the drillability characteristics of rocks under real drilling conditions.

3 Future development of drillability research
(1) Increasing the drilling speed requires a refined classification standard for rock drillability in the future. Currently, humans have drilled into almost all the lithologic strata of nature, from soft to hard to extremely hard. However, the current drillability classification standard is based on the drillability test results of rock samples, mainly from sedimentary rocks, in the 1980s. This standard does not include today’s multiple drill types, and it is extremely difficult to drill the formation lithology. Moreover, many drillability classification methods exist today, with the rapid development of speed-up tools and bit technologies. The classification standards cannot be adapted to guide the rapid development of speed-up tools and bit technologies, and efficient speed-up tools and rock-breaking methods cannot be found using the existing drillability classification standards. Therefore, a refined classification standard for drillability is needed in the future, and the relationship among the classification standard, rock-breaking tools, and rock-breaking methods must be established to provide a scientific basis for modern drilling.

(2) An efficient and rapid drillability test method is needed for future drilling acceleration. Rock drillability produces the most basic scientific data to guide the increase in drilling speed. However, current drillability testing methods are generally destructive, and a large number of rock samples are needed to accurately understand the drillability characteristics of drilling strata. This is often impossible to achieve in drilling engineering because of the high cost and difficulty of coring. In petroleum engineering, only the cores of key sections are tested to meet the various needs of masonry engineering exploration and development because core drillability tests are rare. Therefore, in the future, a highly efficient and rapid method is needed to determine rock drillability.

(3) Increasing the drilling speed of deep and ultra-deep wells requires the evaluation and identification of rock-drillability characteristics in the real physical environment at the bottom of a well. Deep and ultra-deep oil and gas resources are rich in China. Increasing the drilling speed of deep and super-deep wells faces many technical challenges. The physical environment at the bottom of the wellbore has a significant effect on rock drillability. The influence of the real physical environment at the bottom of the well on rock drillability is still not fully understood, nor can the rock drillability characteristics be scientifically evaluated at the bottom of a deep well. Therefore, the technical developments that increase the drilling speed of deep wells are difficult to support. The influence of the real physical environment on rock drillability in deep wells and the scientific evaluation of the drillability characteristics of rocks in real physical environments are possible directions of future development.

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