Optimization and Establishment of Drillability in Gravel Formation

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Abstract. Rock drillability is a comprehensive index used to evaluate the difficulty of drilling and is a basic factor to determine drilling efficiency. Proper evaluation of rock drillability is vital to achieving high-quality and efficient drilling. Currently, the method for determining the drillability of rocks is primarily based on laboratory micro-bit experiments to measure the core's resistance to drilling. This method requires a large number of cores and is expensive, takes a long time to start the test, and often lags behind drilling. Moreover, some people analyzed the relationship between the actual drilling parameters and the mechanics' specific energy of drill bit and established a method to evaluate the rock drillability of rock. Field application proves that the drillability model is poorly correlated with the actual drilling conditions. The value of the actual drilling energy is usually 100–1000 times that of the theoretically calculated mechanics specific energy. Through laboratory experiments, we study the strength and failure characteristics of different gravel sizes and gravel contents with different impact speeds. The matching relationship between rock mass and impact speeds is analyzed. Based on the experimental results, a phase similar to a drill bit and a drilling tool is proposed to support drillability assessment. Under the condition of the same gravel size, with the increase of gravel content, the average cutting speed gradually decreases under the condition of certain cutting force, which is approximately exponential; with the increase of gravel particle size, under the condition of certain cutting force, the average cutting speed rapidly decreases, and the gravel particle size has a decisive impact on the average cutting speed. The above research results can be used to establish a new drillability evaluation model and to optimize the drill bits, drilling tools, and drilling parameters.

1. Introduction
For the drilling of the conglomerate layer, the PDC bit has been used many times. After decades of development, the PDC bit has been greatly improved in terms of the performance of rock breaking ability, penetration rate, and service life in soft-to-medium-hard formations and has been extensively used in drilling operations with significant economic benefits. However, PDC bit is greatly affected by the formation properties because of its poor impact resistance, especially in the drilling of the conglomerate layer, soft hard cross, and other heterogeneous formations. During drilling in conglomerate formation, the cutting teeth are prone to collapse under the continuous impact load, which reduces the cutting efficiency, and finally cannot effectively drill through the conglomerate layer[1-2]. Generally, during drilling conglomerate with PDC bit, it is necessary to trip out and change the bit. After the rock bit is drilled through the formation, the PDC bit is replaced to continue drilling. Such frequent tripping operation needs a lot of operation time, which seriously affects the drilling efficiency.
Since the PDC bit is prone to early damage when drilling conglomerate, it is necessary to perform the corresponding bench test to study the damage mechanism of PDC bit in gravel formation, to provide suggestions for optimizing the drilling effect of PDC bit in conglomerate formation. An experiment will be carried out to study the drilling effect of PDC bit in conglomerate samples under different drilling conditions, analyze the main factors affecting the drillability of the gravel layer, and provide an experimental basis for the optimal design of bit.

Rock drillability is a quantitative index of rock resistance to mechanical crushing[3-4]. It is an important parameter for drilling method optimization and bit selection in the drilling site. It is also the main basis for measuring drilling speed and making the drilling plan. The drillability of a rock depends not only on the characteristics of the rock, including mineral composition, microstructure, and physical and mechanical properties of the rock but also on drilling technology conditions. Among them, the main influencing factor is the mechanical properties of rocks, while the physical properties, mineral composition, and structural characteristics of rocks indirectly affect the drillability by affecting their mechanical properties.

The measurement methods of rock drillability can be roughly divided into two categories: core test method and acoustic data method.

The core test method is a method to test the mechanical properties of rock samples in the laboratory and to obtain the drillability of rock[5-7]. The laboratory experiment method has the defects of lag, long period, and high cost. Although there are some problems, the data obtained by the core test method is still an important basis for bit design and selection. In China, the main methods to evaluate the drillability are the indentation hardness method and the micro-bit drilling method.

The indentation hardness test method is widely used in the geological exploration industry in China, which is used to test the drillability of rocks. The principle of this method is simple. The indentation hardness of the rock sample is expressed by the load value per unit area when the first crushing pit is pressed out on the core surface. The drillability grade of the core can be determined according to the indentation hardness of core measured by experiment. Later studies have shown that the indentation hardness can only represent the ability of rocks to resist the invasion of other objects, but not the ability to resist shear and impact, so it cannot reflect the ability of the rock to resist bit drilling. Moreover, the rock is composed of large and small mineral particles, and there are a lot of pores and fractures between the particles. This structural difference determines that the drillability of rock cannot be determined by the indentation hardness value of some points on the rock. Especially for the conglomerate stratum with serious heterogeneity, the indentation hardness method is more difficult to play a role.

Compared with the micro-bit drilling method, the measured data can well reflect the rock resistance to bit drilling, which is an effective method to obtain the drillability of rock samples in the laboratory, that is, using the rock drillability tester to carry out drilling experiments on the surface of rock samples. The experimental conditions are WOB w = 889.7n, rotating speed n = 55 rpm, and bit diameter d = 31.75 mm. The time required for drilling depth h to be 2.4 mm was recorded during the experiment. The drillability grade of the rock sample is the logarithm with the base of 2 for each drilling time.

However, due to the small effective coverage and not-very-deep drilling depth, the drillability value of conglomerate obtained by the micro-drilling method for conglomerate formation with serious lithological heterogeneity often cannot reflect the overall drillability of the conglomerate. Therefore, the method needs to be improved.

The core experiment method, also known as the direct method, is feasible to determine the drillability of a certain section of rock stratum, but it is difficult to obtain a complete drillability profile. To obtain a complete drillability profile, indirect methods are generally used to obtain the drillability of formation, mainly acoustic data method[8-13].

The main factors affecting the speed of acoustic wave propagation in the formation are rock hardness and rock fragmentation[14-18]. According to the experimental analysis, in most cases, the harder the rock is, the fewer the fractures are, and the faster the sound wave propagation speed is. Therefore, the drillability of a certain formation can be reflected by the value of the sound wave logging data of a certain formation, and an empirical model of the relationship between the sound wave logging data of a certain well section and the drillability of the formation can be established by using the model
drillability profile of the well section. The field shows that, compared with the core experiment method, a continuous drillability profile can be obtained by using acoustic logging data, and a lot of energy and financial resources can be saved, which is of great significance to the drilling operation. However, for those rock intervals with complex structure and mineral composition, the drillability predicted by this method is quite different from the real value. For example, in the gravel stratum, the acoustic data cannot reflect the influence of the existence of acoustic gravel particles on the drillability of the stratum, which shows that the acoustic data method has limitations in showing the drillability of the stratum with serious anisotropy.

2. Experimental Device and Scheme
According to the properties of the bottom conglomerate, the conglomerate is simulated to make rock samples, and PDC single-tooth simulation platform is used to measure the rock breaking speed of single tooth under the same lateral force under the condition of fixed depth, as the evaluation standard of gravel drillability, and based on this, the main control factors of gravel formation drillability are analyzed.

2.1. Preparation of Experimental Test Sample
It is very difficult to study the gravel content by comparing the two factors. Moreover, the conglomerate layer encountered during drilling is mostly argillaceous cementation, and the cementation is relatively loose. After cement consolidation, the drillability of sandstone and that of mudstone are close to each other. Therefore, the method of cement cemented gravel is selected to simulate the conglomerate in this experiment. In this way, according to the needs of the experiment, we can make conglomerate rock samples with different gravel particle sizes and gravel contents. The relationship between the drillability of conglomerate and its two influencing factors can be quantitatively analyzed by the drillability test.

The cement rock sample of dimensions 15cm × 15cm × 15cm is made by the cement-cementation-gravel method to simulate the conglomerate. The cement model is 425, the gravel composition is SiO2, the density is 2.66 g/cm³, and the water-cement ratio is 0.4. The control variable method is used to control the median particle size and gravel content in the rock samples. Five groups of rock samples were designed in the experiment, the gravel content was 10%, 20%, 30%, 40%, and 50%, and the median particle size was 3, 6, 12, 16, and 24 mm, respectively. Before the preparation of the rock sample, the mass of gravel, cement, and water (see Table 1) should be calculated according to the volume of the rock sample, the volume content of gravel, the density of gravel, and the water-cement ratio (see Table 1). Each rock sample is cured for 20 days to achieve the final strength. To calibrate the accuracy of the experimental data, a pure cement sample was made with the same type of cement.

| Group number | Gravel volume content (%) | Gravel particle size | Median gravel mass (kg) | Cement mass (kg) | Water mass (kg) |
|--------------|---------------------------|----------------------|------------------------|-----------------|----------------|
| 1            | 10                        | 3mm,6 mm,12          | 0.9                    | 4.16            | 1.67           |
| 2            | 20                        | mm,16 mm             | 1.80                   | 3.70            | 1.48           |
| 3            | 30                        | and 24 mm            | 2.69                   | 3.24            | 1.30           |
| 4            | 40                        |                      | 3.60                   | 2.78            | 1.11           |
| 5            | 50                        |                      | 4.49                   | 2.31            | 0.93           |

2.2. Experimental Apparatus
The drillability evaluation experiment is mainly carried out on the self-developed single-tooth PDC composite chip test bench. Figure 1 shows the test bench. The test bench can complete the triaxial stress of the composite under different cutting speed conditions. At present, the cutting speed range of the experimental bench is 0.01–0.8 m/s, which can meet the test requirements. Moreover, the tool holder base of the PDC composite test bench can be adjusted after changing the roll angle and caster angle of the composite; the triaxial stress of the composite under different rolls and caster angles was measured.
According to the mechanical penetration rate in the drilling process, the bit penetration depth of the simulation well is 2 mm, assuming that the lateral cutting force of the bit is fixed at 200 N, the simulation sample is placed on the test bench to test the scratch speed, and the speed can be equal to the mechanical penetration rate.

![Image](image_url)

**Fig 1.** Cutter head caster adjustment device

![Image](image_url)

**Fig 2.** Schematic of the experimental setup

2.3. **Experimental Procedures**

During the test, the rock sample with a flat surface is fixed on the rock sample clamping device, the feeding depth of PDC cutting teeth is adjusted by adjusting the planer tool rest, and the cutting depth is fixed by locking the tool rest. When starting the planer, the ram of the planer drives the PDC cutting teeth to impact the rock sample at a certain speed, to simulate the cutting process of the cutting teeth in the actual drilling. In the cutting process, axial force and tangential force sensor are used to measure the axial impact force FN and tangential impact force FC of PDC cutting teeth at the moment of impact. The data acquisition system records and displays the test data, as shown in Figure 2.

To analyze the influence of rock indentation hardness, cutting parameters, and cutting speed on the force of cutting teeth, cutting tests were carried out with different cutting depths (1.0, 1.5, 2.0, 2.5, and 3.0 mm), different back dip angles (5°, 10°, 15°, 20°, and 25°), different cutting speeds (0.52, 0.62, 0.92, and 1.12 m/s), and different gravel content.

3. **Main Influencing Factors on Drillability of Gravel Layer**
3.1. Analysis of Experimental Results
From the results above, it can be found that, under the condition of the same gravel particle size, with the increase of gravel content, the average cutting speed gradually decreases under the condition of certain cutting force, which has an approximately exponential relationship; with the increase of gravel particle size, under the condition of certain cutting force, the average cutting speed decreases rapidly, and the gravel particle size is decisive for the average cutting speed influence. Based on the experimental results, it can be seen that the main factor affecting the drillability of the gravel layer is the particle size of gravel.

![Fig 3. Relationship between gravel size, gravel content, and ROP](image)

3.2. Analysis of the Damage Factors of PDC Bit in Gravel Layer
Firstly, according to the force direction and effect of the cutting teeth, the forces on the cutting teeth can be divided into tangential impact force, axial impact force, and lateral impact force. The corresponding effects on the bit are torsional vibration, axial vibration, and drill whirl. When the bit is drilling in the conglomerate layer, when the bit is drilling at a relatively high speed, if the gravel is suddenly drilled, the cutting teeth will be subjected to strong instantaneous load, and the torsional vibration will be caused by the fluctuation of drill pipe torque. Because PDC cutting teeth are brittle materials, the strain under impact load is very small, resulting in PDC microcracks appearing on the surface or inside of the composite, which further reduces the impact resistance of the PDC composite. Moreover, the twist vibration of the bit makes the drilling situation more unstable, which further intensifies the damaging effect of the impact load on the cutting teeth of the bit. Under the continuous impact load, the PDC composite chips will eventually collapse or even break, resulting in the loss of cutting ability. At the same time, when drilling hard gravel at the bottom of the hole, if the cutting teeth of the bit slide over the gravel surface, the bit will be subjected to additional axial impact force in the axial direction, resulting in axial vibration. The axial vibration also has great harm to the composite sheet. Because of the residual stress at the interface between the PDC layer and the tungsten carbide matrix, the PDC will be caused by the axial vibration. The cutting teeth lose the cutting ability due to the peeling of the layer and the substrate. Finally, during the period of drilling the conglomerate layer, the bit will also be affected by the lateral force. If the lateral force of the bit is very large, there will be no movement between the bit and the borehole wall due to the friction effect, and the reverse rotation will occur. Because the cutting teeth of the bit are designed for the forward force, the bearing capacity of the reverse force is poor, so the rotation of the bit is easy to cause the composite chip to peel off and lose the cutting ability.
Generally speaking, when the matrix has a small cementation strength or a small gravel particle size, the cutting teeth can easily peel the gravel from the matrix when cutting the rock layer; when the cementation strength of the matrix is large or the gravel is large, the cutting teeth must cut hard gravel or slide over the gravel surface during drilling. In the two cases, the impact load on the cutting teeth is different. Compared with the second rock breaking method, the impact load generated by the first rock breaking method is smaller; in particular, the second rock breaking mode will cause the drill string axial vibration and lateral sliding, which is more dangerous. This explains why the size of gravel has a decisive effect on the drillability of gravel.

4. Conclusions and Suggestions
Under the condition of the same gravel size, with the increase of gravel content, the average cutting speed gradually decreases under the condition of a certain cutting force, which is approximately exponential; with the increase of gravel particle size, under the condition of a certain cutting force, the average cutting speed decreases rapidly, and the gravel particle size has a decisive impact on the average cutting speed.

The main factor that affects the life of bit in gravel layer is the size of gravel. The cementation strength of the matrix is small or the particle size of gravel is small. When cutting the rock layer with cutting teeth, the gravel will be easily peeled off from the matrix. When the cementation strength of the matrix is large or the gravel is large, the cutting teeth must cut hard gravel or slide over the gravel surface during bit drilling, resulting in drilling. The head is destroyed ahead of time.

5. References
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