Experimental Research on Rotation-Percussion Drilling of Diamond Bit Based on Stress Wave

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Abstract. Rotary-percussive drilling is a common form of drilling in geotechnical engineering. In order to study the effect of rotational speed and impact speed on rock-breaking efficiency, a drilling simulation platform developed by ourselves and a drill pipe equipped with diamond bit were used to conduct simulated drilling experiments. By monitoring the stress wave during drilling, the strain, stress and energy changes at different rotational speeds and impact velocities can be obtained, and the optimal drilling parameters can be determined. The results show that both speed and impact velocity have direct influence on the drilling process. When the rotational speed is kept constant, the drilling efficiency increases first and then decreases with the increase of the impact velocity. When the impact velocity remains constant, the drilling efficiency decreases with the increase of rotating speed. With the increase of rotational speed, the optimal impact velocity also increases. It is helpful to improve the drilling efficiency by reasonable choice of speed and impact speed.

1. Introduction
Drilling is a common construction process in underground geotechnical engineering. How to improve the efficiency of drilling and rock breaking is also a long-standing problem in engineering. The traditional method is to obtain the physical and mechanical properties of rock and soil by in-situ testing or laboratory analysis after coring, and then to optimize drilling according to the test results. However, these methods are generally time-consuming and costly. According to statistics, the cost of traditional methods can account for 10%-35% of the total cost of geotechnical engineering project [1].

There are many factors affecting the drilling efficiency, such as rock mass physical and mechanical parameters (compressive strength, elastic modulus, Poisson's ratio, cohesion, etc.), drilling rate, drilling rig parameters (rotation speed, axial pressure, torque, etc.) all have a great impact on the drilling efficiency [2,3]. Based on this situation, some scholars adopted the drilling process monitoring technology to collect and analyze the parameters in the drilling process, so as to find a method to improve the drilling efficiency [4,7].

In geotechnical engineering exploration, the energy principle has been used in formation identification and lithological judgment [8,9], and bad geological conditions, such as weak strata and faults, can be predicted [10] [11]. In terms of impact response, the impact experiment based on Split Hopkinson Pressure Bar (SHPB) has been widely used in the aspects of end friction, stress test, rock
mass composite loading, rock mass deformation control, etc., and has become one of the standard methods of material dynamics [11]. In the impact test on the rock mass, it is shown that the rock mass will produce internal stress waves under the impact load, and the parameters will change in the narrow area through which the stress waves pass, which is directly related to the strength of the rock mass [12,15]. In terms of rock breaking efficiency of impact drilling, some scholars have carried out theoretical and experimental studies from the perspectives of energy and drilling mechanism, and made some progress [16,17].

Based on previous studies, this paper intends to study the law of rotation-impact rock breaking process by controlling the impact velocity and rotation speed on the drilling simulation platform developed by ourselves from the perspective of stress wave energy, so as to provide reference for improving the drilling efficiency.

2. Experimental Research

2.1. Experimental process and method principle

The drilling system adopts a self-developed and modified impact-rotation device based on Hopkinson rod (SHPB). The drill rod with a diamond drill is used to impact the high-speed rotating sample to simulate the drilling process of the rotary impact of the drill rod. The system consists of an air compression launch system, a high-precision fixed platform, an ultra-dynamic resistance strain gauge, a high-speed controllable rotation system, and a data acquisition and analysis system. The schematic diagram of the system structure is shown in Figure 1.

The main process of the experiment is broken down as follows: 1. The air compressor releases the pressure under the set air pressure, so that the impact rod ("bullet") in the launcher tube has a certain initial velocity; 2. The impact rod impinges on the equal diameter drill pipe, the drill pipe gains speed and generates compressive stress waves in the impact rod and drill pipe; 3. The compressive stress wave in the impacting rod transmits to the top and generates a reflected stress wave at the top, and then the reflected stress wave transmits down and merges with the stress wave in the drill pipe; 4. The stress wave after the intersection in the drill pipe is transmitted downward, and the compression displacement $\Delta_1$ is formed at the top of the drill pipe; 5. The stress wave with the wavelength of $2L_d$ in the drill pipe propagates downward with the velocity of $c_0$, and produces reflected stress wave after impacting the rock body in the rotating state, so that the compression displacement $\Delta_2$ is generated again in the drill pipe. The impact rod velocity was calculated by the microsecond counter velocity measurement system, and the drill pipe tension and compression strain were recorded by the dynamic strain gauge connected.
with the tension strain gauge attached to the surface of the rod. The experimental setup and wave system diagram are shown in Figure 2.

Figure 2. Experimental device and wave system diagram.

The basic principle of the experiment is the propagation law of one-dimensional stress wave (literature). When the drill pipe hits the rock mass, the stress wave will be generated inside the drill pipe. By attaching the strain gauge on the drill pipe surface and connecting it according to the Wheatstone bridge principle, the compression displacement caused by the stress wave will produce a slight voltage change. By monitoring, recording, analyzing and calculating the voltage signal, the strain, stress and energy during the collision between drill pipe and rock mass can be obtained.

Before the experiment, there is a certain reserved width $\delta$ between the diamond bit and the drilled rock. When the ramming rod hits the drill pipe, incident waves will be generated in the drill pipe, but at this time, the drill bit is not in contact with the rock being drilled. The incident wave reflects from the drill pipe to the contact surface of the rock mass to form a tensile wave. When the incident wave is completely reflected, the reserved width is just closed, so the reserved width should be equal to the displacement of the drill pipe after the impact pipe hits the drill pipe.

The stress amplitude generated in the drill pipe during the impact of the equal diameter rod is only related to the length of the impact rod (bullet), the velocity and the material characteristics of the rod (elastic modulus $E$, density $\rho$, etc.), but not to the length of the drill pipe. Therefore, when the impact rod with the length of $L_0$ collided with the drill pipe with the impact velocity $V_0$, the reserved width between it and the drill pipe is:

$$\delta = \frac{L_0V_0}{c_0}$$  \hspace{1cm} (1)

$$c_0 = \frac{E}{\sqrt{\rho}}$$  \hspace{1cm} (2)

Where, $c_0$ is the stress wave velocity and $E$ is the elastic modulus of drill pipe.

A subsubsection. The paragraph text follows on from the subsubsection headin The relationship between the strain measured by the strain gauge $\varepsilon(t)$ and the display voltage:

$$\varepsilon(t) = \frac{1}{2} \varepsilon_p = \frac{1}{2} \frac{2U_0K_2}{U_0K_1K_2} = \frac{2U_x}{U_0K_1K_2}$$  \hspace{1cm} (3)

Where $\varepsilon_p$ is the actual strain value, according to Wheatstone bridge principle, the formula can be obtained: $\varepsilon_p = 2\varepsilon$, $K_1$ is the strain gauge sensitivity coefficient (2.00), $U_0$ is the supply bridge voltage (4 V), $U_x$ is the oscilloscope display voltage value, $K_2$ is the gain value on the strain gauge, namely the amplification factor (500).
Based on the strain value calculated by the above formula, and combined with the stress-strain relationship, the stress (t) in the drill pipe can be obtained as follows:

\[ \sigma(t) = E \varepsilon(t) = \frac{2E\varepsilon_x}{\varepsilon_0 K_1 K_2} \]  

(4)

Based on the above formula, the stress changes in the drill pipe during the impact can be obtained by voltage monitoring of the impact-rotation process.

2.2. The experimental scheme

The impact rod used in the experiment is made of the same material as the drill pipe, both of which are high-strength steel with an elastic modulus of 210GPa and a density of 7850kg/m³. The diameter of the rod body is 25mm, the length of the impact rod is 200mm and the length of the drill pipe is 1800mm. The drill bit adopts PDC bit with high strength steel matrix and diamond-impregnated, with an internal diameter of 25mm and an external diameter of 35mm. In order to simulate drilling impact, the PDC bit and the high-strength steel drill pipe were connected by interference assembly.

By adjusting the cylinder pressure value, the impact rod can produce different firing speeds. Meanwhile, the velocity \( V_0 \) when the impact rod and drill pipe collide can be measured by laser speedometer. The measured relation curve between cylinder pressure \( P \) and impact velocity \( V_0 \) is shown in Figure 3. The regression analysis of the scatter plots of the two shows that there is an obvious linear relationship between cylinder pressure \( P \) and impact velocity \( V_0 \), and the regression formula is as follows:

\[ V_0 = 0.39062P + 5.98364 \quad R^2 = 0.99 \]  

(5)

Where, \( V_0 \) is the final impact velocity of the impact rod, unit m/s; \( P \) is the cylinder emission pressure, psi.

![Figure 3. Pressure velocity curve.](image)

By adjusting the cylinder pressure, the final impact velocity is controlled as 7.2m/s, 9.4m/s, 10.8m/s, 12.2m/s, 13.8m/s and 16m/s. The rotational speeds were set to 32rad/min, 66rad/min, 15rad/min, 225rad/min and 315rad/min through the rotation control system. The test rock mass is the natural rock mass retrieved from the top of the coal mine. After each impact, new samples are used, and no cycle test is conducted to ensure that the test rock mass is not affected by previous impacts. Three samples were tested under the same working condition, and the curves with stable and representative results were taken for analysis.

C. Specification of rock mass to be tested

Of the natural rock by rock cutting machine processing, make it a size is \( \Phi100 \times 100 \) mm cylinder, and the smooth processing on both ends of the rock mass, make the surface smooth error within 0.02 mm.
3. Experimental Results and Analysis

3.1. Image of impact experiment
Before each impact, the integrity of the rock mass to be tested is first determined to ensure that there is no obvious fracture or failure of the rock mass to be tested. In figure 4, (a) and (b) respectively represent the measured data graphs of oscilloscope with the impact velocity of 7.2 m/s and 12.2 m/s under the operating condition of 32 rad/min, and the abscissa represents the time (unit: ms) and the ordinate represents the voltage value (unit: V). In the figure, channel 1 records the voltage change caused by the shear strain gauge on the drill pipe, channel 2 records the voltage change caused by the tensile and compression strain gauge on the drill pipe, and channel 3 records the audio variable of the collision process. This paper focuses on the analysis of voltage changes caused by the tensile and compressive strains of the second channel. It can be seen from the figure that the oscilloscope voltage amplitude is significantly different under two different impact velocities.

References are cited in the text just by square brackets [1]. Two or more references at a time may be put in one set of brackets [3, 4]. The references are to be numbered in the order in which they are cited in the text and are to be listed at the end of the contribution under heading references, see our example below.

![Figure 4](image_url)  
(a) The impact velocity is 7.2 m/s  
(b) The impact velocity is 12.2 m/s

Figure 4. Oscilloscope images at different impact velocities.

Taking the rotational speed of 32 rad/min as an example, the voltage value at 6 different impact velocities is converted into the stress value, and the first incident stress wave and reflected stress wave are taken as shown in Figure 5. It can be seen from Figure 5 that both the incident stress wave and the reflected stress waveform at different impact velocities are presented as rectangles, and the amplitude of the stress wave increases with the increase of the impact velocity, indicating that both the incident stress and the reflected stress will increase with the increase of the impact velocity.

![Figure 5](image_url)  
Figure 5. Stress wave images at different impact velocities.
3.2. Analysis of experimental results

This part analyzes the stress wave energy. For the calculation of stress wave energy, it is not only related to the stress value, but also to the wavelength and time. The calculation formula of stress wave is as follows:

\[
E = \frac{\rho c}{E} \int_0^{t_p} \sigma^2 dt
\]

Where, \(E_i\) and \(E_r\) are the energy of incident and reflected stress waves respectively, \(\sigma_i\) and \(\sigma_r\) are incident and reflected stress waves respectively, \(E\) is the elastic modulus of the drill pipe, \(A\) is the cross-sectional area of the drill pipe, \(\rho\) is the density of the drill pipe, \(c_0\) is the propagation velocity of sound wave in drill pipe, \(t_p\) is the duration of the pulse stress wave.

From equation (6), it can be seen that the energy of stress wave is not only related to the inherent characteristics of drill pipe (cross-sectional area, elastic modulus, and acoustic velocity), but also depends on the stress magnitude and duration, both of which can be obtained from Figure 5.

For each impact process, the more the stress wave energy loss is, the more the energy absorbed by the rock mass is. Therefore, the analysis can be made from the perspective of energy loss, so as to find out the optimal rock-breaking parameters. The formula for calculating the energy loss rate of a single impact process is as follows:

\[
\varphi = \frac{E_i - E_r}{E_i} \times 100\%
\]

In the formula: \(\varphi\) is the energy loss rate of single impact. The higher the energy loss rate, the higher the drilling efficiency.

According to formulas (6) and (7), the statistics of experimental results are shown in table 1.

Table 1. Stress wave energy and its loss rate under different working conditions.

| Speed of rotation (rad/min) | Energy (J) | Impact speed (m/s) |
|-----------------------------|-----------|-------------------|
|                             | 7.2       | 9.4               | 10.8 | 12.2 | 13.8 | 16   |
| Incident wave               |           |                   |      |      |      |      |
| 32                           | 16.36     | 39.29             | 66.13 | 88.97 | 103.52 | 131.49 |
| Reflected wave              | 7.45      | 16.89             | 29.65 | 40.96 | 48.48 | 62.85 |
| Attrition rate              | 54.46%    | 57.01%            | 55.16% | 53.96% | 53.17% | 52.20% |
| 66                           | 16.28     | 39.26             | 66.08 | 89.06 | 102.89 | 130.97 |
| Incident wave               | 7.68      | 17.54             | 30.26 | 41.69 | 50.31 | 64.59 |
| Reflected wave              | 52.83%    | 55.32%            | 54.21% | 53.19% | 51.10% | 50.68% |
| Attrition rate              |           |                   |      |      |      |      |
| 155                          | 16.41     | 38.79             | 67.12 | 88.65 | 104.87 | 132.48 |
| Incident wave               | 8.15      | 18.65             | 32.15 | 42.78 | 52.13 | 66.43 |
| Reflected wave              | 50.34%    | 51.92%            | 52.10% | 51.74% | 50.29% | 49.86% |
| Attrition rate              |           |                   |      |      |      |      |
| 225                          | 16.37     | 40.05             | 66.32 | 88.15 | 103.29 | 132.45 |
| Incident wave               | 8.24      | 19.65             | 32.46 | 43.08 | 51.89 | 67.23 |
| Reflected wave              | 49.66%    | 50.94%            | 51.06% | 51.13% | 49.76% | 49.24% |
| Attrition rate              |           |                   |      |      |      |      |
| 315                          | 16.34     | 39.45             | 65.92 | 89.04 | 102.69 | 133.59 |
| Incident wave               | 8.56      | 20.51             | 33.78 | 45.32 | 51.98 | 68.64 |
| Reflected wave              | 47.61%    | 48.01%            | 48.76% | 49.10% | 49.38% | 48.62% |

According to the calculation results in table 1, the relationship between stress wave energy and rotational speed under different impact velocities is analyzed, as shown in Figure 6. It can be seen from FIG. 6 that at the same rotational speed, both the incident wave energy and the reflected wave energy will increase with the increase of the impact velocity, and the relationship is approximately linear, but the slope of the two lines is different.

For the same impact velocity, the incident wave energy value at different rotating speeds is almost unchanged. This is because the incident wave has been formed before the impact between the drill pipe and the rock mass, so it has nothing to do with the rock mass rotation speed. However, the reflected wave energy value will increase with the increase of the rotational speed, resulting in the energy loss rate decreases with the increase of the rotational speed, which also indicates that the rotational speed will affect the rock-breaking efficiency.
In order to study the rock-breaking efficiency at different impact velocities, the energy loss rate at 5 rotational speeds was analyzed, as shown in Figure 7. It can be seen from the figure that the energy loss rate shows a changing process of increasing and then decreasing at different rotational speeds: at the lowest speed (32 rad/min), the impact velocity with the highest energy loss rate was 9.4 m/s. With the increase of the speed (66 rad/min to 225 rad/min), the impact velocity with the highest energy loss rate gradually changed to 10.8 m/s and 12.2 m/s. At the maximum speed (315 rad/min), the impact velocity with the highest energy loss rate was 13.8 m/s. This indicates that the rotation speed will affect the selection of the optimal impact velocity of rock mass in this experiment, which provides a theoretical basis for the efficient rotary drilling process.

When the impact velocity is relatively low, the impact of rotational speed on the energy loss rate will be greater: when the impact velocity is 7.2 m/s, the lowest and highest energy loss rates are 22.3% and 37.47%, respectively, with a difference of 15.17%. When the impact velocity was 16 m/s, the difference was only 8.11%.

It is worth noting that the energy loss rate at the same rotational speed will decrease with the increase of the rotational speed, which does not mean that the rotational impact is counterproductive to rock breaking. On the contrary, the shear strength of most rock masses is lower than the compressive strength, and the shear failure of rock masses during drilling is a very common failure form, so the shear force caused by rotation can theoretically improve the rock-breaking efficiency. However, the rock mass used in this experiment is a brittle rock mass, and the contact time between the drill bit and the rock mass is very short during the impact process, so the contact time of the impact is shorter under high rotation speed, and the shear failure is difficult to play a role. Therefore, in this experiment, compared with shear failure, the rock mass is more sensitive to impact failure, so the improvement of rotational speed cannot bring about higher rock-breaking efficiency.

Figure 6. Stress wave energy at different impact velocities.
4. Conclusion

Based on the drilling simulation test platform designed by ourselves, by adjusting the impact velocity and rotation velocity in the simulation drilling process, the rotation-impact test based on the stress wave monitoring technology was carried out on the deep coal mine roof rock mass, and the drilling process optimization analysis based on the energy analysis was carried out. The results show that:

1. The wave shapes of incident stress wave and reflected stress wave in the process of drill pipe collision are rectangular, which indicates the propagation characteristics of stress in drill pipe. Furthermore, the stress wave energy is linearly correlated with the impact velocity;

2. Under the same rotational speed, the energy loss rate of stress wave increases first and then decreases with the increase of impact velocity, and the higher the energy loss rate is, the higher the drilling efficiency is. It is beneficial to improve the rock breaking efficiency to choose the impact velocity reasonably;

3. Under the same impact velocity, the rotational speed will affect the energy loss rate. In this experiment, the energy loss rate decreases with the increase of the rotating speed, which indicates that the rock mass in this experiment has higher efficiency of drilling and rock breaking at low rotating speed;

4. With the increase of rotational speed, the optimal impact velocity also increases. When the rotational speed is 32rad/min, the optimal impact velocity is about 9.4m/s, with the increase of the rotational speed, the optimal impact velocity gradually increased, at the rotational speed of 315rad/min, the optimal impact velocity reached 13.8m/s.

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