Experimental analysis and parameter optimization of PDC bit for rock drilling trolley

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Abstract. The design parameters of PDC bits for rock drilling trolley have not been studied in depth and it is lack of theoretical research basis. So the service life of the bits for tunnel tunneling construction cannot meet the design and application requirements. Taking three-arm rock drilling trolley as the experimental platform, the key parameters of PDC bit crown profile shape, caster angle, cutting tooth size, tooth arrangement density, inner cone angle, outer swing angle and crown top shape for rock drilling trolley are designed by combining the optimum design method, empirical numerical value and experimental correction. The key parameters were optimized and improved through a set of manufactured bits, and a set of drills were manufactured again for the following experiment. The experimental data in second stage shows that the broken and drop defects of the improved bits are greatly reduced. The drilling depth is significantly increased, and the service life is also improved, which meets the requirements of design and operation.

1. Introduction
Mechanical rock drilling trolleys used for tunnel construction at home and abroad are generally equipped with hydraulic or pneumatic rock drills. And the drill bit usually uses carbide or tungsten alloy cylindrical teeth. The researches on PDC bit are carried out in recent years. Specially, when the rock hardness and the bit cost reach a reasonable interval in tunnel construction, the trolley using cutting drilling method has a great living space. The development preconditions for cutting drilling trolley is whether the bit design can meet the application requirements.

As the main rock crushing tool in rock drilling process, the bit quality, and the bit’s adaptability to rock characteristics and blasting technology will directly affect the drilling speed, drilling quality and blasting cost.

At present, the drilling equipment used in tunnels are pneumatic rock drill (hand-held or leg-supported) and full hydraulic rock drilling trolley. Using cemented carbide and tungsten alloy as the working part of the bit, the bit is characterized by its small diameter, about 44mm~51mm, and its single hole depth is less than 5.5m. The case of tunnel blasting hole construction using PDC bit cutting technology has not been reported yet. The reason is that there is no rock drilling trolley using cutting technology in current engineering application. In 2016, a prototype of ZS316 three-arm rock drilling trolley was developed by a Tianjin company according to the cutting method. This topic will use this trolley to carry out relevant experiments.
2. Bit design

2.1. Bit crown design
According to the basic requirements of the crown design, the theoretical crown curve equation of PDC bit is deduced considering the principles of equal cutting, equal wear and equal power [1]. According to the established equation, computer-aided design method and the actual requirement of this subject, the design scheme with three-wing layout, three equal-pitch and equal-weight external teeth and one internal tooth is adopted in this paper.

Previous studies show that the force on the cutting teeth and the rotating torque is the smallest at 10 degrees. The longitudinal force, cutting force and torque all increase with the increase of caster angle [2]. Therefore, this design is aimed at the case of sandstone and limestone with compressive strength between 40Mp and 110Mp, and chooses the caster angle of 17 degrees. The lateral rotation angle of the cutting teeth is taken as an empirical value of 10 degrees. The diameter of the outer segment is 13.44 mm, the diameter of the inner segment is 10 mm and the thickness is 8 mm. The internal teeth are sagged and the inner cone angle is 7.5 degrees. The internal concave bit is formed utilizing the difference of the inner and outer teeth diameters. The maximum contour size of the bit is 46mm, the shoulder size is 44mm, and the shoulder is welded with three diameter-preserving sheets. The outer cone angle is composed of the arc of the outer tooth sheet and the tangent of the shoulder.

2.2. Bit matrix design
The matrix of the drill bit is milled with 45# steel and connected with the drill pipe with the inner threads of the straight ladder. Water hole arrangement is 5x5 mm. Two holes in the middle are parallel to the central axis. Three holes in the circumference are inclined, and the axis is facing the center of the working face of the outward gear sheet, which is conducive to cooling and slag discharge. Twenty experimental bits were produced by Henan Yellow River Cyclone Company according to the design requirements.

3. Experimental test

3.1. Experimental site
The experimental site is located in Huilongwan Village, Xiema Town, Beibei District, Chongqing City. It is a three-lane road tunnel connecting the outer ring highway of Chongqing with the one-way traffic from Xiema to Caijia Section. It consists of two parallel tunnels, left and right, with a length of 4200m. Left cave was chosen in this experiment. The project progress was 1500 meters. The stratum was limestone. Quartz crystals were visually observed and it shown that the 10% quantity of the whole structure. To avoid affecting the normal work of the construction side, a traffic tunnel was provided as the experimental site, as displayed in Fig.1. The geological report shows that the rock compressive strength in this area is 90Mp-110Mp.

Fig 1. Experimental site
3.2. Experimental equipment parameters

The experimental device is a ZS316 three-arm fully hydraulic remote control drilling rig with three independent drill arms. Each drill arm is driven by a hydraulic cylinder, and the drill pipe is driven by a hydraulic motor to rotate the drill bit. There is no impact device. A high-pressure pump provides 1.5 MP of pressure, with a flow of 220L water for slag discharge. The trolley is adjusted to the following parameters according to the requirements of bit design:

|                | No.1 drill arm | No.2 drill arm | No.3 drill arm |
|----------------|----------------|----------------|----------------|
| Propelling force (N.m) | 900            | 800            | 700            |
| Rotational torque (N.m)  | 450            | 450            | 450            |
| Rotational speed (r/min) | 400            | 400            | 400            |
| Water pump            | 1.5Mp pressure and 220L flow |

The work field was shown in Fig.2.

Fig 2. Experiment equipment

3.3. Experimental data and results of the first stage

The experiment lasted 56 days in two stages. In the first stage, 20 bits were tested. Each drill was inspected and the drill bit was replaced if two pieces were damaged or the drilling time was more than 8 minutes. The experimental data are shown in Table 2.

3.4. Improvement of bit design

According to the analysis of the damaged bit data, 2 # and 4 # pieces are most damaged. The reason is that the bit structure is not good. The transition between outer cone and shoulder is unreasonable, resulting in contact with hole wall points on the circumference. The bit's weak ability to resist transverse force during drilling process causes radial runout. And the No. 4 tooth has only one space, so that the ability to prevent bit from transverse movement is weak. In the process of collapse, a large irregular radial force is applied to the bit. As a result, the bit's circumference jumps too much, and the bit hits the rock, resulting in the fragmentation of the external teeth. At the same time, the internal teeth also collapse due to the squeezing of the intermediate pillar. According to the analysis reasons, the technical improvement of outer slice cutting and inner slice chamfering is made. The three-dimensional diagrams of improved bit were established in Fig.3.
Table 2. Experimental data in first stage

| No. | Drill arm | Depth of drilling long borehole (m) | Average hole forming time | Total footage (m) | Damaged parts |
|-----|-----------|-----------------------------------|---------------------------|------------------|---------------|
| 1   | 1         | 4.2                               | 5'17''                    | 84               | 2#, 4# broken |
| 2   | 2         | 4.2                               | 5'31''                    | 96.6             | 2# broken, 4#drop |
| 3   | 3         | 4.2                               | 5'47''                    | 88.2             | 1#, 2# broken |
| 4   | 1         | 4.2                               | 4'49''                    | 96.6             | 2# broken, 4# drop |
| 5   | 3         | 4.2                               | 5'43''                    | 117.6            | 2# broken, 4# broken |
| 6   | 1         | 4.2                               | 5'01''                    | 105              | 2# drop, 3# drop |
| 7   | 2         | 4.2                               | 5'10''                    | 96.6             | 1#, 2# broken |
| 8   | 3         | 4.2                               | 5'50''                    | 113.4            | 2# broken, 4# drop |
| 9   | 1         | 4.2                               | 5'11''                    | 117.6            | 2# broken, 3# drop |
| 10  | 3         | 4.2                               | 5'47''                    | 138.6            | 1#, 2#, 4# broken |
| 11  | 2         | 4.2                               | 5'43''                    | 105              | 2# broken, 3# drop |
| 12  | 1         | 4.2                               | 4'47''                    | 113.4            | 2# broken, 4# drop |
| 13  | 2         | 4.2                               | 5'12''                    | 151.2            | 2# broken |
| 14  | 3         | 4.2                               | 5'31''                    | 88.2             | 2# broken, 4# drop |
| 15  | 2         | 4.2                               | 5'30''                    | 105              | 2# broken, 3# drop |
| 16  | 3         | 4.2                               | 5'55''                    | 117.6            | 2# broken, 1# drop |
| 17  | 2         | 4.2                               | 5'43''                    | 113.4            | 1#, 2#, 4# broken |
| 18  | 1         | 4.2                               | 5'13''                    | 138.6            | 2# broken, 4# drop |
| 19  | 3         | 4.2                               | 5'57''                    | 96.6             | 2# broken, 4# drop |
| 20  | 2         | 4.2                               | 5'42''                    | 105              | 2# broken, 1# drop |

It was found that the feed speed was not ideal and could not meet the design requirements during the first stage experiment. The service life of drill bit is low. Through the data analysis, all the causes of drill bit damage are broken or drop, and none of them is abandoned due to the decrease of drilling efficiency after wear and tear.

![Three-dimensional diagrams of improved bit](image-url)

**Fig 3. Three-dimensional diagrams of improved bit**
3.5. Experimental data and results of the second stage

**Table 3.** Experimental data in second stage

| No. | Drill arm | Depth of drilling long borehole (m) | Average hole forming time | Total footage (m) | Damaged parts |
|-----|-----------|------------------------------------|---------------------------|------------------|---------------|
| 1   | 1         | 4.2                                | 3'19''                    | 264.6            | 1#,2#,3#,4# wear and broken |
| 2   | 2         | 4.2                                | 3'36''                    | 298.2            | 1#,2#,3#,4# wear and broken |
| 3   | 3         | 4.2                                | 3'24''                    | 239.4            | 1#,2#,3#,4# wear and broken |
| 4   | 1         | 4.2                                | 2'49''                    | 155.4            | 1#,3#,4# wear and broken, 2# drop |
| 5   | 3         | 4.2                                | 3'43''                    | 277.2            | 1#,2#,3#,4# wear and broken |
| 6   | 1         | 4.2                                | 3'08''                    | 214.2            | 1#,2#,3# wear and broken, 4# drop |
| 7   | 2         | 4.2                                | 3'14''                    | 239.4            | 1#,2#,3#,4# wear and broken |
| 8   | 3         | 4.2                                | 3'40''                    | 247.8            | 1#,2#,3#,4# wear and broken |
| 9   | 1         | 4.2                                | 3'17''                    | 197.4            | 1#,2#,3#,4# wear and broken |
| 10  | 3         | 4.2                                | 3'27''                    | 268.8            | 1#,2#,3#,4# wear and broken |
| 11  | 2         | 4.2                                | 3'26''                    | 256.2            | 1#,2#,3#,4# wear and broken |
| 12  | 1         | 4.2                                | 3'47''                    | 306.6            | 1#,2#,3#,4# wear and broken |
| 13  | 2         | 4.2                                | 3'19''                    | 210              | 1#,2#,3#,4# wear and broken |
| 14  | 3         | 4.2                                | 3'33''                    | 264.6            | 1#,2#,3#,4# wear and broken |
| 15  | 2         | 4.2                                | 4'12''                    | 399              | 1#,2#,3#,4# wear and broken |
| 16  | 3         | 4.2                                | 3'45''                    | 239.4            | 1#,2#,3#,4# wear and broken, 4# drop |
| 17  | 2         | 4.2                                | 3'34''                    | 264.6            | 1#,2#,3#,4# wear and broken |
| 18  | 1         | 4.2                                | 3'31''                    | 268.8            | 1#,2#,3#,4# wear and broken |
| 19  | 3         | 4.2                                | 3'46''                    | 348.6            | 1#,2#,3#,4# wear and broken |
| 20  | 2         | 4.2                                | 3'52''                    | 378              | 1#,2#,3#,4# wear and broken |

The experimental data of the second stage show that the improved scheme is feasible, and the drilling speed, depth and service life all meet the design requirements. Compared with the data in first stage, the PDC obtained from the second experimental data is invalid because of the wear, avoiding accidental invalidation due to unreasonable structure.
4. Summary and prospect

4.1. Conclusion
In this paper, the key parameters of PDC bits for rock drilling rigs are designed by combining site experiments with empirical numerical combination. A set of available parameters are determined by optimizing the parameters. The finished bits are manufactured according to the design parameters. After testing, the optimization scheme is re-designed according to the experimental results to meet requirements. The following conclusions are summarized:

(a) The crown diameter of drill bit for rock drilling is 44mm. The caster angle is 17 degrees. The size of cutting teeth is 3-13.44mm, and the corresponding inner teeth is 1-10mm. The cone angle is 7.5 degrees, and the lateral rotation angle is 10 degrees.

(b) PDC bit for rock drilling rig after cutting edge and chamfering of inner teeth has better drilling efficiency and service life than untreated bit. Through innovative design of cutting edge and chamfering, various parameters have been greatly improved, which has practical significance for mass production.

(c) When the rock hardness and compressive strength are less than 120 Mp, the cost and efficiency of PDC bit cutting drilling method for rock drilling trolley is better than that of traditional percussive bit drilling trolley.

(d) The research results have practical feasible guiding for the development of rock drilling jumbo.

4.2. Outlook
Due to the limitation of site, time and funds, the following problems will be further studied, which are of great significance for the development of cutting and drilling jumbo.

(a) It is also necessary to study the key parameters of 4-wing or 5-wing bit structure.

(b) The finite element analysis is introduced to simulate the bit structure, which can greatly shorten the development time and improve the experimental efficiency.

(c) The welding reliability of PDC bits and the manufacturing process of bit blanks will be considered.

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