Petroleum Science 22 (2025) 5114–5127

Contents lists available at ScienceDirect

Petroleum Science

journal homepage: www.keaipublishing.com/en/journals/petroleum-science

Original Paper

Optimization of rate of penetration through improved bit durability and extended directional nozzle

Chao-Chao Feng [a], Yong Li [b], Wei Liu [a,*], De-Li Gao [a,**]

[a] MOE Key Laboratory of Petroleum Engineering, China University of Petroleum (Beijing), Beijing, 102249, China
[b] China Oilfield Services Limited, Tianjin, 300459, China

A R T I C L E I N F O

Article history:
Received 16 November 2024
Received in revised form
10 October 2025
Accepted 12 October 2025
Available online 15 October 2025

Edited by Jia-Jia Fei

Keywords:
ROP improvement
Enhanced drilling parameters
PDC bit
Bit durability
Extended directional nozzle

A B S T R A C T

The enhanced drilling parameters and custom-designed polycrystalline diamond compact (PDC) bits have greatly improved both rate of penetration (ROP) and footage. Then how to further improve the bit's ROP and how to deal with the side effects caused by the enhanced drilling parameters remain a challenge. In this work, the single-cutter rock-cutting tests and full-sized bit drilling tests were conducted to investigate the effects of rock types, drilling parameters, and bit designs on ROP. The results showed that in the easy-to-drill formations, the enhanced drilling parameters had a more pronounced effect on improving the bit's ROP than the optimizations of bit designs such as changing the cutter shape and size. On the other hand, in the hard-to-drill formations, smaller-sized and shaped PDC cutters combined with high-torque tools offered a promising approach to increase ROP. To further improve ROP and footage, two innovative approaches were introduced: improving the bit durability without compromising ROP to ensure one-trip drilling, and using extended directional nozzles together with enhanced hydraulic parameters. The bit durability was improved by optimizing the cutter shape and diamond materials, which helped complete the single-run footage of 2986 m in the field trial of Shengli Oilfield. It was also found that the extended directional nozzle was less effective under conventional hydraulic parameters, but increased the ROP by 32.1% under enhanced hydraulic parameters because of improving jet impact performance through reduced jet diffusion. The findings provided insights for ROP improvement in the oil and gas drilling operations.

1. Introduction

Improving ROP and then reducing drilling costs are core objectives in the oil and gas drilling applications. With the continuous advancement of global oil and gas exploration and development, drilling in complex and hard-to-drill formations at deep and ultra-deep depths has become common, accompanied by an increasing demand for cost reduction and drilling efficiency enhancement. In this context, issues such as low ROP and short footage per run during drilling operations are becoming more severe, and effective technical solutions need to be urgently explored (Wang et al., 2022).

The ROP is governed by various factors, including formation characteristics, bit structure, drilling parameters, wellbore configuration, drilling fluid properties, and drilling technologies (Gao et al., 2023). Serving as the essential rock-breaking tool and the core medium for transforming drilling energy into effective rock breakage, the bit plays a critical role in determining ROP. The bit-centered strategy for enhancing ROP focuses on the selection and optimization of bit structures and auxiliary rock-breaking tools, coupled with the systematic adjustment of drilling parameters, and has been extensively studied.

The weight on bit (WOB), rotary speed (RPM), and flow rate are key operational parameters of the drilling process that serve as the direct sources of mechanical and hydraulic energy for bit rock-breaking. The PDC cutter of the bit penetrates the rock under the applied WOB, which governs both the depth of cut (DOC) and the volume of rock removed, thereby directly influencing ROP.

* Corresponding author.
** Corresponding author.
E-mail addresses: wei.liu@cup.edu.cn (W. Liu), gaodeli@cup.edu.cn (D.-L. Gao).
Peer review under the responsibility of China University of Petroleum (Beijing).

https://doi.org/10.1016/j.petsci.2025.10.007
1995-8226/

Increasing WOB generally resulted in a linear improvement in ROP until the founder point was reached, beyond which the relationship between WOB and ROP became nonlinear due to dysfunctions such as bit balling, bottom hole balling, and severe vibrations (Walker et al., 1986; Dupriest and Koederitz, 2005). And traditional drilling parameters also defined a 'nominally' linear relationship between RPM and ROP (Judzis et al., 2006). In addition, when the rotary speed reached ultra-high levels (above 2000 rpm, ultra-high-speed rotary drilling was shown to reduce drilling costs by lowering equipment and energy requirements. In ultra-high-speed drilling, the mechanical specific energy (MSE) decreased with increasing RPM. The rock-breaking mode also changed, with a higher occurrence of brittle failure in the formation, although such high rotary speeds might accelerate bit wear (Gao et al., 2020; Li et al., 2024a).

In terms of hydraulic energy, flow rate directly governs the hydraulic power and bottom-hole cleaning efficiency. Moslemi and Ahmadi (2014) emphasized that increased flow rate enhances hydraulic horsepower per square inch (HSI), which in turn significantly improves ROP. For instance, raising HSI from 1.18 to 3.74 was associated with a 37% increase in ROP and a 77% increase in jet velocity. Field studies showed that higher HSI was particularly effective in soft formations such as the Catoosa shale, where it contributed to improved bit cleaning and cuttings transport efficiency (Wells et al., 2008). Meng et al. (2016) established a systematic drilling hydraulics optimization method, which optimized the nozzle diameter, flow rate and drill pipe size to increase the bit pressure drop and bit-specific hydraulic horsepower, resulting in ROP improvements ranging from 10.5% to 80%.

In addition to enhancing bottom-hole cleaning and cuttings transport efficiency, hydraulic energy also assists rock breaking and improves overall efficiency. High-pressure water jets induced microcracks within the rock through mechanisms such as impact pressure and the water wedge effect, and, when coupled with the mechanical cutting action of PDC cutters, enabled synergistic rock fragmentation (Ciccu and Grosso, 2014). And the high-pressure water jet assisted drilling has been widely studied and applied in drilling engineering (Liu et al., 2020; Wang et al., 2023; Li et al., 2024b, 2025), which has demonstrated ROP improvements ranging from 35% to 200% in siltstone field tests (Liao et al., 2015).

The established relationships between core drilling parameters and ROP, coupled with the continuous advancement of rig equipment, have driven the field application of enhanced drilling parameters to improve ROP. The application of enhanced drilling parameters has contributed significantly to the advancement of shale oil exploration in North America (Doak et al., 2018). Moreover, in geothermal drilling, Dupriest and Noynaert (2022) employed a progressive optimization strategy by increasing the WOB from 226.8 to 317.5 kN and adjusting the rotary speed from 40 to 50 rpm, resulting in a substantial increase in drilling footage from 226 to 643 m and achieving a maximum ROP of 29 m/h. Inspired by these developments, drilling practices in China have adopted similar strategies. In shale gas fields such as Changning, Weiyuan, and Fuling, drilling parameters have been intensified by 20%–30% relative to conventional values. For instance, in a Ø215.9 mm wellbore in the Changning shale gas field, the implementation of enhanced drilling parameters led to an 86% increase in ROP compared to offset wells using conventional parameters (Yuan et al., 2022). Although the effectiveness of enhanced drilling parameters in improving ROP has been widely demonstrated, the optimization process remains largely dependent on engineering experience and lacks systematic theoretical and experimental support. In addition, increasing attention has been directed toward the adverse effects associated with high-energy drilling conditions, such as accelerated bit wear, tool failure, and instability in downhole dynamics.

Drilling efficiency is also influenced by the cutting structures and hydraulic designs of the bit. The PDC cutter has been widely recognized as a key component that governs the overall bit performance. Materials advancement, which has improved the impact resistance and wear resistance of PDC cutters, has also facilitated the development of shaped cutters (Liu et al., 2025a, 2025b, 2025c). The various types of shaped cutters have changed and optimized the rock-breaking modes of conventional cylindrical cutters, enabling a combination of multiple rock-breaking mechanisms, namely shearing, crushing, plowing, etc., and correspondingly improving the rock-breaking efficiency and the service life of cutters and bits (Liu and Gao, 2023). The stinger cutter operated under a point-loading mechanism and was characterized by a diamond layer twice as thick as that of conventional PDC cutters, offering superior impact resistance and wear tolerance. Field tests showed that bits equipped with stinger cutters achieved high ROP and extended footage in interbedded lithology in North America, hard carbonates and abrasive sandstone in the Middle East, and carbonate/chert formations in Kazakhstan and Russia (Azar et al., 2013; German et al., 2015; Pak et al., 2016). The axe-shaped cutter improved the rock-breaking efficiency by combining shear, extrusion, and point-loading actions through its ridged structure. The ridged structure not only lowered the cutting force but also improved impact resistance due to the reinforced diamond layer at the cutting edge (Negm et al., 2016; Shao et al., 2021). This design achieved an average ROP increase of 70% compared with conventional bits in hard and interbedded formations (Gumich et al., 2017). Izbinski et al. (2019) proposed a double-chamfered cutter design based on the principle that increased chamfering reduces crack propagation and fragment detachment in the diamond layer, thereby extending cutter service life. The scribe cutter featured a pointed cutting tip and a relieved substrate, which enabled it to generate higher stress on the rock to efficiently initiate and propagate fractures. And the relieved substrate reduced contact between the cutter body and the formation, thereby mitigating frictional energy losses during cutting. Compared with conventional cutter bits, greater efficiency was observed for the scribe cutter bit in field tests conducted in harder formations such as carbonates and anhydrites (Rahmani, 2019; Shamea et al., 2020). Shaped PDC cutters with unique geometric features exhibit enhanced rock-breaking efficiency. However, their effectiveness also depends on the placement specifications in the drill bit manufacturing process. Liu et al. (2025c) demonstrated that adjusting the tip orientation could effectively improve the rock-breaking efficiency of both shaped PDC cutters and their bits.

For the hydraulic structure design of drill bit, Moslemi et al. (2014, 2015) investigated the influence of nozzle size, nozzle arrangement, nozzle number, and waterway profile on cuttings-transport efficiency. Based on these findings, a PDC bit customized for shale formations was developed, featuring improved nozzle orientation, optimized blade height, and integrated fluid-guiding structures to mitigate bit balling commonly encountered in shale drilling. Rahmani et al. (2016) proposed a novel flow path and nozzle geometry to enhance the cooling and cleaning efficiency of PDC cutters. Similarly, Schnuriger et al. (2017) introduced curved nozzle designs that facilitated improved fluid coverage of the cutting face, leading to enhanced ROP and reduced bit balling risks. Based on the jet impingement theory and jet pump mechanisms, Chen et al. (2016) developed a jet mill bit that reduces the size of cuttings through impact, fluid wedging, and micro-erosion mechanisms, thereby improving suspension and transport capacity. Building on this design, a modified jet mill bit with an emphasis on pressure reduction was subsequently developed. This bit incorporated a rearward jetting structure to generate a localized low-pressure zone at the bit bottom, which enhanced bottom-hole cleaning efficiency (Chen et al., 2020). The technological advancements in both cutter shape and hydraulic structure have collectively laid the foundation for the development of customized PDC bits that integrate mechanical and hydraulic optimizations to meet the demands of complex formations.

As drilling depth increases, inefficient energy transfer reduces the energy available for rock breaking at the bit. Meanwhile, the formations become significantly more difficult to break, resulting in a decrease in ROP. To address this challenge, various auxiliary rock-breaking tools have been developed to increase the energy delivered to the bit, including positive displacement motors (Samuel and Miska, 2000; Ochoa et al., 2009; Lu et al., 2024), turbodrills (Staley et al., 2011; He et al., 2021; Gao et al., 2024), and axial-torsional coupled impact drilling tools (Xu et al., 2016; Liu et al., 2018; Xi et al., 2023). These tools operate by converting the hydraulic energy of the drilling fluid into mechanical energy to assist the bit in breaking the rock, either by increasing RPM, providing additional impact loads, or ensuring sufficient torque.

Enhanced drilling parameters and auxiliary rock-breaking tools increase the drilling energy delivered to the bit for rock-breaking, while optimized bit structures improve the efficiency of drilling energy utilization. And enhanced drilling parameters and custom-designed PDC bits have made great advances in improving the ROP and footage for a single run, then there are two issues that need to be faced, how to further improve drilling efficiency when the enhanced drilling parameters have reached the upper limit of the existing rig equipment, and how to solve the side effects caused by enhanced drilling parameters, such as premature bit failure.

To solve these two issues, the single-cutter rock-cutting tests and full-sized bit drilling tests were utilized in this work to systematically investigate the effects of drilling parameters, rock type, and cutter design on the ROP, providing more rigorous theoretical and experimental guidance for drill bit selection and drilling parameter optimization. Additionally, optimizations of both the cutter selection and hydraulic structure were also proposed to address practical challenges encountered in the field. These optimizations were subsequently validated through field trials. The findings could provide insights for continued advances in the oil and gas drilling operations.

2. Experimental setup and procedures

2.1. Multi-index evaluation of PDC cutter

PDC cutters are the key component of the bit, which greatly determine the ROP and durability of the bit. A series of single-cutter rock-cutting tests were conducted in the laboratory to evaluate various performances of PDC cutters, including rock-breaking efficiency, ROP potential, wear resistance, and impact resistance (Liu et al., 2024). The single-cutter rock-cutting test was conducted using a vertical turret lathe (VTL) to assess the cutter's rock-breaking efficiency. The cutting forces and rock cuttings of PDC cutters were collected under various DOCs. MSE was utilized to evaluate the rock-cutting efficiency of the tested PDC cutters. However, MSE alone cannot predict the ROP performance of shaped cutters and their bits. To address this limitation, the ROP potential index was used to predict ROP performance based on the results of single-cutter rock-cutting tests. The wet VTL test was employed to investigate the wear resistance of the PDC cutters. The cutters were subjected to a controlled sliding distance under constant DOC and linear velocity. After multiple passes, the volume loss of the tested cutter was measured using a 3D optical profiler. The dry VTL test was used to evaluate the cutter's thermal stability. The difference between the dry VTL test and wet VTL test was whether there was coolant during the cutting. Impact resistance was evaluated using a progressive drop test (PDT), which subjected the cutter to controlled impact forces. PDC cutters were tested with a gradually increased impact energy to mimic impact loads during drilling, evaluating the energy levels at which crack or failure occur. Impact resistance was first assessed in the cutter face direction, but all shaped cutters yielded poor resistance, making it difficult to distinguish the difference among them. Then, the focus shifted to the cutter's tip impacts using carbide as the impactor. Initial crack energy (ICE) refers to the energy level at which the cutter first develops cracks, while fracture failure energy (FFE) is defined as the energy required for significant failure, typically characterized by a damaged area greater than or equal to 30% of the total diamond area. This test helped assess the durability of the cutter under dynamic loading conditions during actual drilling operations.

As shown in Fig. 1, various shaped cutters with the same diameter of 16 mm and height of 19 mm were investigated in this work, including the cylindrical cutter (with 0.2 and 0.4 mm chamfers), 165 axe-shaped cutter, 135 axe-shaped cutter, dual-chamfer cutter, scribe cutter, and 150 and 160 tri-ridged cutters. PDC is a super-hard composite material consisting of a polycrystalline diamond (PCD) layer and a cemented tungsten carbide (WC-Co) substrate. The influence of PCD material properties was also considered. The 160 tri-ridged cutter included two diamond mixes (#A and #B), while the others utilized the same diamond mix, #A. Based on the above laboratory tests of single PDC cutters, the multi-index evaluation plot was built as shown in Fig. 2 to show key properties of PDC cutters and help the operators make appropriate selections to fulfill the multiple needs of actual drilling operations under downhole conditions. These tests could also be used to emphasize the importance of optimizing the cutter shape and diamond matrix to alleviate wear and impact damage under drilling conditions using enhanced drilling parameters.

2.2. Full-sized bit drilling test

To further validate the findings from the single-cutter rock-cutting tests and examine the performance of various bit designs, the full-sized bit drilling tests were conducted using the horizontal drilling rig. The effects of the rock type, WOB, RPM, and cutter shape on the ROP were investigated. As shown in Fig. 3, the horizontal drilling rig consists of several key components: a power system, a control system, a drilling system, a data acquisition system, a measurement while drilling (MWD) sub, and a rock sample with dimensions of 2 m $\times$ 0.35 m $\times$ 0.35 m. The power system is responsible for providing hydraulic energy to drive the drilling operation. The control system regulates the WOB and RPM. The drilling system is composed of the drill bit, drill pipe, and water injection pipe. A high-pressure drilling fluid pump circulates the fluid through the system to cool the bit and remove rock cuttings. The cuttings are separated from the fluid in the cuttings collection module for further analysis. The setup is capable of applying a maximum WOB of 250 kN, a torque up to 10,000 N·m, and a rotational speed ranging from 45 to 160 rpm. During the tests, the rotational speed was set at 75 rpm while WOB was changed as a key variable. In this work, clean water was employed to transport the cuttings and to cool the bit during drilling. Throughout the test, drilling parameters, including WOB, torque, RPM, and vibration, were recorded in real time by the MWD sub, providing precise tracking and feedback on the bit conditions during the drilling process.

During the drilling tests, the bit and drill pipe were rotated, while the drilling fluid was pumped through the tail of the drill pipe, flowing through the internal passage of the drill pipe and exiting from the bit nozzles. Once a stable drilling condition was

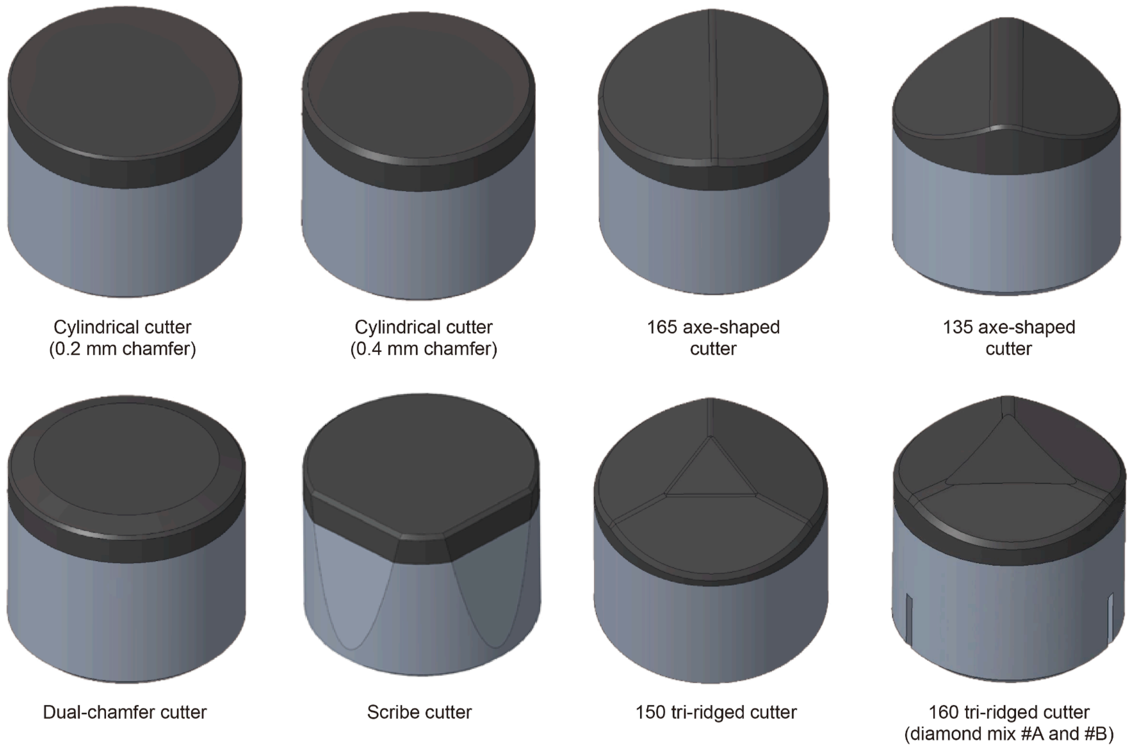

Fig. 1. 3D models of various shaped cutters for testing.

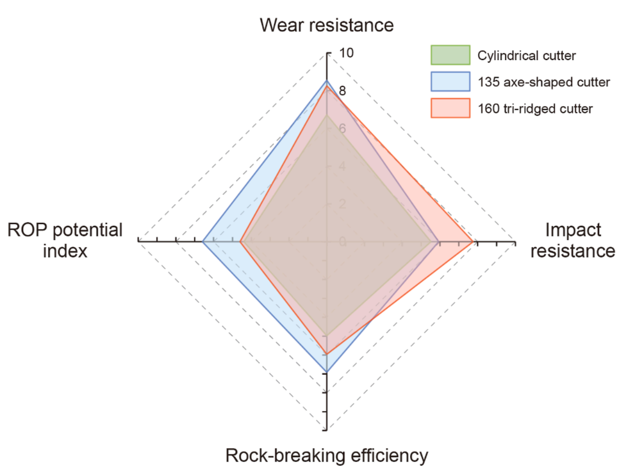

Fig. 2. Multi-index evaluation of PDC cutters.

achieved in which all cutters were fully engaged with the rock, the WOB, torque, RPM and ROP were measured and recorded in real time. Due to bit vibrations during the drilling process, some fluctuations in WOB and torque data were observed, as shown in Fig. 4, but these fluctuations remained within a small range. Therefore, the average values of WOB and torque in the stable stage of the drilling process were used for further analysis.

2.3. Experimental materials

The PDC bit used in the tests had a diameter of Ø215.9 mm and featured four blades. Two types of bit bodies were used, one with the cutter size of Ø16 mm, and the other one with the cutter size of Ø19 mm. Except for the cutter size, these two types of bit bodies shared the same design, including the bit profile, the same cutter spacing, and the same back rake angle of 15° and side rake of 0°. Two types of rock samples were used in this work, sandstone and granite. The sandstone was characterized by good drillability with an average uniaxial compressive strength (UCS) of 89 MPa while the granite exhibited poor drillability with an average UCS of 204 MPa. The 135 axe-shaped cutter, 165 axe-shaped cutter, 160 tri-ridged cutter, scribe cutter, and cylindrical cutter were respectively brazed onto the bit body, respectively, and then used for the full-sized bit drilling tests. Before each test, only the cutters on the cone, nose, and shoulder areas were replaced using the same type of PDC cutters while the cutters on the gauge were removed to reduce the influence of the gauge on the test results.

3. Results and discussion

3.1. Rock-breaking mechanism of PDC bits

The rock-breaking process of PDC bits can be theoretically divided into three stages: penetration, rotary cutting, and cuttings evacuation, as shown in Fig. 5. Each of these stages is influenced by specific drilling parameters. The penetration process is mainly governed by the WOB and cutter shape, which determine how the cutter can effectively engage with and crush the rock. The stable shearing and cutting process is mainly driven by torque and RPM, which enable the continuous rock fragmentation and affect the drilling rate. The evacuation process of rock cuttings depends on the drilling fluid flow rate and the hydraulic designs of the bit.

To achieve efficient drilling with a PDC bit, it is essential that the drilling parameters are adequately optimized to support the bit's ability to penetrate and shear the rock. Additionally, sufficient hydraulic energy must be provided through the drilling fluid to ensure effective and rapid removal of cuttings. Based on the rock-breaking mechanism of PDC bits, it is concluded that the WOB,

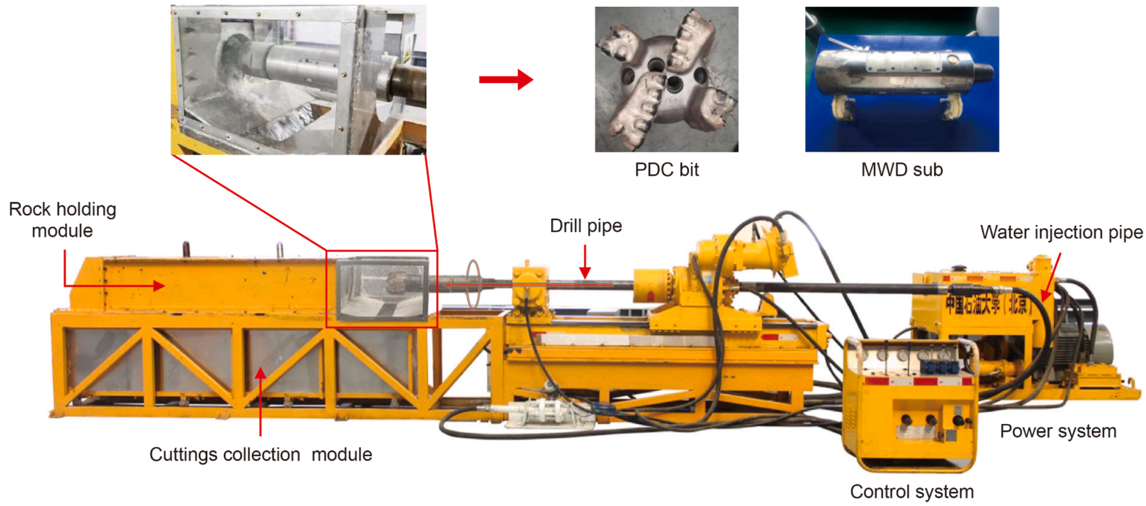

Fig. 3. Horizontal drilling rig used for the full-sized bit drilling tests.

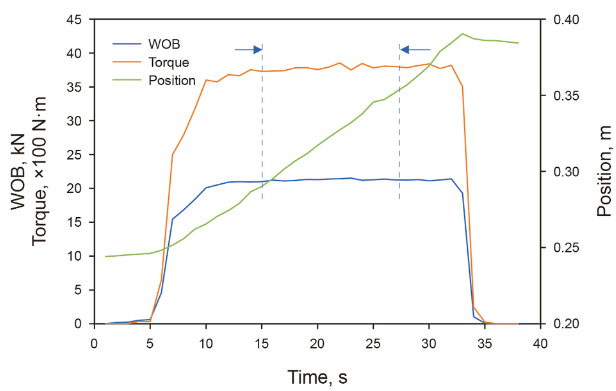

Fig. 4. MWD-recorded data curves of WOB, torque, and bit position over time.

RPM, torque, flow rate, cutter shape, and bit design are the key factors influencing the ROP. WOB, RPM, torque, and flow rate serve as the sources of energy required for rock breaking by the bit, whereas cutter shape and bit design contribute to improving the efficiency of energy utilization. Understanding their respective roles facilitates targeted optimization strategies for improving overall drilling efficiency. The effects of these factors on the ROP are analyzed in detail as follows.

3.2. Effects of rock type, WOB and cutter size on ROP

PDC bits deployed with Ø16 mm and Ø19 mm cylindrical cutters, respectively, were used to drill the sandstone and granite samples on the horizontal drilling rig. The test results are shown in Fig. 6. It is noted that within the parameter range of this work, a positive linear relationship is observed between WOB and ROP. In the single-cutter rock-cutting test, the WOB corresponds to the axial forces. Previous studies have demonstrated that when the cutter is in a high-efficiency cutting state, an increase in axial force leads to an increase in DOC, a decrease in MSE and an improvement of rock-breaking efficiency (Liu et al., 2025d).

As shown in Fig. 6, in tests conducted to drill the sandstone, when the WOB is increased from 20 to 30 kN, the ROP for the bit deployed with Ø16 mm and Ø19 mm cutters increases by 91.1% and 182.9%, respectively, while increasing the cutter diameter from Ø16 mm to Ø19 mm under the same WOB of 30 kN only results in a 73.6% increase in ROP. For granite, increasing the WOB from 20 to 25 kN improves the ROP by 52.4% and 165.8% for the Ø16 mm and Ø19 mm cutters, respectively, and changing the cutter size from Ø19 mm to Ø16 mm at a WOB of 25 kN results in an 18.5% increase. These results indicate that the effect of increasing WOB is significantly greater than the effect of altering cutter size while drilling both the easy and hard formations. It can be inferred that increasing the total drilling energy input for rock breaking

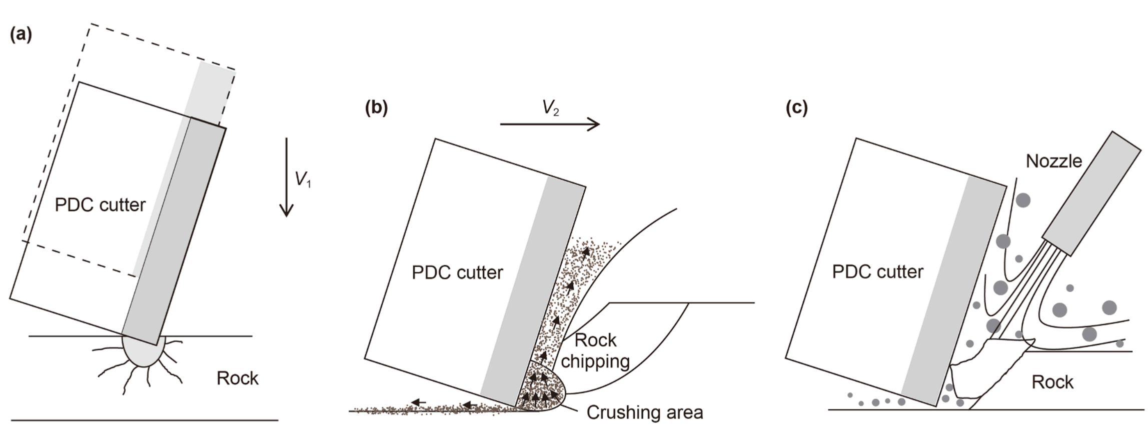

Fig. 5. (**a**) Penetration, (**b**) rotary cutting and (**c**) cuttings evacuation.

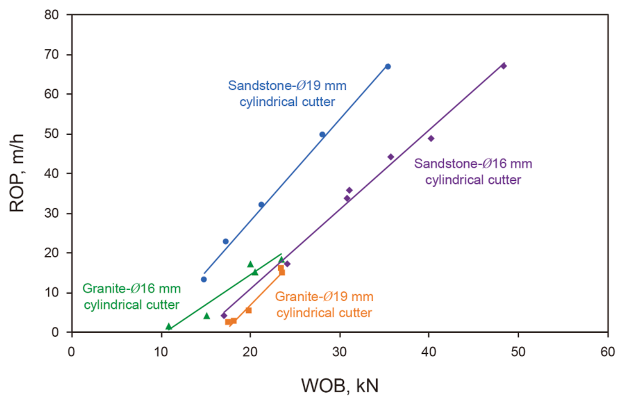

Fig. 6. Effects of rock type, WOB and cutter size on the ROP.

contributes more substantially to ROP improvement than enhancing the efficiency of energy utilization. It is also noted that the larger cutter size such as Ø19 mm is more beneficial for improving the ROP while drilling the easy-to-drill formations.

Fig. 6 also shows that, compared to sandstone, the bit deployed with Ø16 mm cutters exhibits a higher ROP while drilling the granite than the bit deployed with Ø19 mm cutters at the WOB ranging from 10 to 25 kN. Therefore, smaller cutter sizes such as Ø13 mm and Ø16 mm are more effective for improving ROP in hard-to-drill formations. In addition, due to the torque limitation of the horizontal drilling rig, higher WOB used to drill the granite could not be conducted. Notably, Fig. 6 reveals a trend in which the ROP of the bit deployed with Ø19 mm cutters gradually exceeds that of the Ø16 mm cutter bit with increasing WOB, suggesting that the rock-breaking efficiency of the larger-diameter cutter is enhanced under sufficient drilling energy.

As shown in Fig. 7, a positive linear correlation between WOB and torque is observed while PDC bits drill both sandstone and granite. In addition, lower torque is required for both the bit deployed with Ø16 mm and Ø19 mm cutters in sandstone than in granite. And the torque difference between these two cutter sizes increases with increasing WOB while drilling the sandstone. This trend is the same as the observed ROP behavior in sandstone when altering cutter sizes. At a WOB of 20 kN, the torque required for the bit deployed with Ø16 mm and Ø19 mm cutters is 1209 and 1366 N·m, respectively, with a difference of 157 N·m. When the WOB increases to 30 kN, this difference expands to 383 N·m.

In contrast, drilling granite requires higher torque than sandstone under the same WOB. Fig. 7 shows that at a WOB of 20 kN, the torque required for the bits deployed with Ø16 mm and Ø19 mm cutters is 2976 and 2184 N·m, respectively, with a difference of 793 N·m. When the WOB increased to 25 kN, the torque difference decreases to 148 N·m, which is consistent with the corresponding variation in ROP. Therefore, improving ROP in hard-to-drill formations requires not only a higher WOB but also the tools with a higher torque output, such as a high-torque downhole motor.

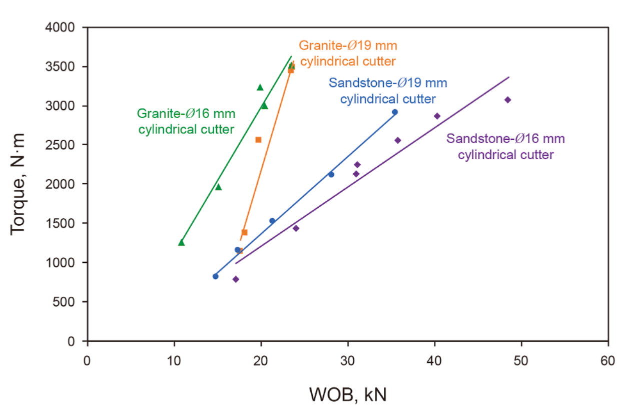

Fig. 7. Effect of rock type and cutter diameter on the WOB-torque relation.

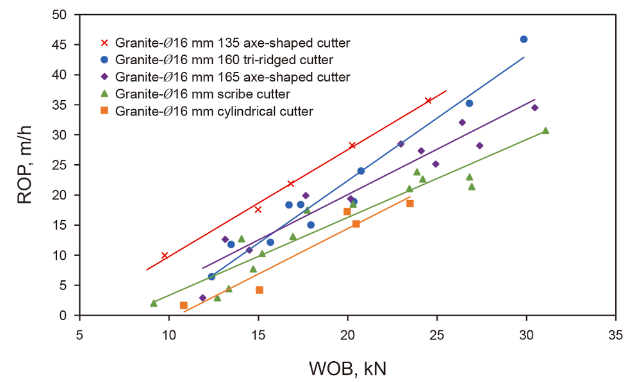

Fig. 8. Effect of cutter shape on the WOB-ROP relation.

As shown in Fig. 8, when drilling the granite, the bits deployed with shaped cutters achieve higher ROP compared to the cylindrical cutter bit at the same WOB, demonstrating the greater rock-breaking efficiency of shaped cutters. The ROP of the five types of PDC bits, at a WOB of 20 kN, is ranked from highest to lowest as follows: 135 axe-shaped cutter, 160 tri-ridged cutter, 165 axe-shaped cutter, scribe cutter, and cylindrical cutter. A sharper cutter bit correlates with a steeper WOB-ROP slope, indicating a stronger ability to increase ROP. According to Fig. 8, the ROP ranking of the five types of shaped cutter PDC bits varies as WOB changes. When WOB exceeds 30 kN, the performance of the tri-ridged cutter and the 165 axe-shaped cutter intersect, indicating that the tri-ridged cutter bit has greater potential for improving ROP with increasing WOB. The result shows that the rock-breaking performance of shaped cutter bits is not unchanged but varies with the changes of the drilling parameters, which is consistent with the single-cutter rock-cutting test results (Liu et al., 2025d). Fig. 8 also demonstrates that increasing the WOB is more effective on the improving ROP than solely altering the cutter shape of bit in hard-to-drill formations.

3.3. Effect of RPM on ROP

To further analyze the effect of RPM on ROP while drilling in sandstone, the bit deployed with Ø16 mm cylindrical cutters was employed, with the RPM ranging from 75 to 120 rpm, and the result is shown in Fig. 9. It can be seen that a higher ROP is

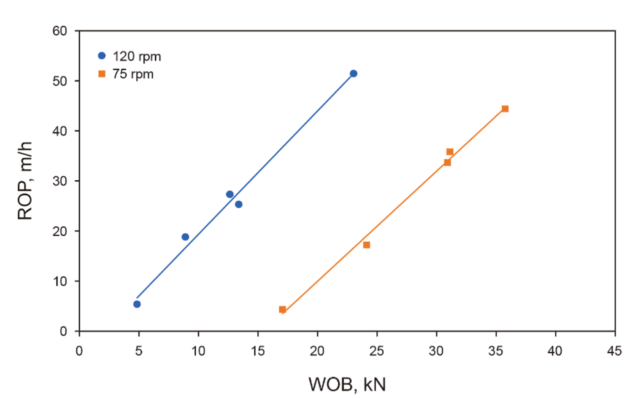

Fig. 9. Effect of RPM on the WOB-ROP relation.

achieved under the same WOB as the rotational speed increases. According to the ROP formula (ROP = PPR × RPM), when the bit penetration per revolution (PPR) remains constant, an increase in RPM results in a higher volume of rock being removed per unit time, thereby increasing the ROP.

In sum, comparing the effects of rock type, drilling parameters, and bit design on the ROP, the rock type exerted the most significant effect, followed by the drilling parameters (WOB, RPM, etc.), and finally the bit designs such as the cutter shape and size. Because the rock type cannot be altered, efforts to improve ROP should primarily focus on optimizing drilling parameters, followed by the optimization of cutter and bit designs. Therefore, enhancing both the total drilling energy input and the efficiency of energy utilization represents the effective strategy. That is, the combination of enhanced drilling parameters with custom-designed PDC bits for the target formations hold considerable potential for improving ROP.

4. How to further improve ROP and footage

As previously discussed, enhanced drilling parameters can significantly improve the ROP. However, they may exacerbate the bit damage, thereby reducing overall drilling efficiency. Therefore, new methods were required to further increase ROP and footage, one of which was to improve bit durability without compromising ROP. Additionally, optimizing the bit's hydraulic structure could enhance cuttings removal and cooling efficiency, supporting sustained improvements in the ROP.

4.1. Bit durability improvement

The Binnan region is located in the Shengli Oilfield in eastern China, featuring formations with good drillability. Enhanced drilling parameters have been implemented to optimize the drilling efficiency. The comparison of ROP before and after the implementation of enhanced drilling parameters in the Binnan region is illustrated in Fig. 10. As shown, the adoption of enhanced drilling parameters has resulted in a significant increase in ROP with the average ROP rising from 45.8 to 78.2 m/h, representing an increase of 70.7%.

In terms of lithologic distribution, the gravel is present at the bottom of the Guantao Formation and at the top of the Dongying Formation. In wells located in the Binnan region in which enhanced drilling parameters were not applied, the gravel did not emerge as the primary cause of the premature bit failure. However, in wells in which enhanced drilling parameters were employed, severe damage was observed on the bits, particularly in the shoulder area, resulting in multiple trips. Fig. 11 illustrates the damaged bit used in B37-8-X4 well in Binnan region, which was scrapped due to ring-out, along with the gravel collected from the well. The enhanced drilling parameters were used in this well, compared to adjacent wells which were drilled in 2014, including an increase in surface rotational speed from 60–90 to 100–120 rpm, the use of more powerful motors, and an increase in WOB from 40–80 to 80–120 kN. Higher RPM caused the cutters at the bit to have higher linear velocity, and thus the impingements by the same gravels caused larger impact energy and worse damage on PDC cutters, especially at the shoulder area. The increased drilling energy resulting from enhanced parameters not only contributed to higher ROP, but also imposed greater impact loads on the bit.

To address the bit failure issue shown in Fig. 11, improving the bit's impact resistance without compromising ROP is a key objective. Therefore, the effects of cutter shape and PCD material properties on the impact resistance were investigated. The test results are presented in a box plot, as shown in Fig. 12. It is observed that increasing the chamfer size from 0.2 to 0.4 mm on cylindrical cutters can enhance the impact resistance of PDC cutters, while a dual-chamfer design further improves the impact resistance. Among the tested samples, the 160 tri-ridged cutter with diamond mix #B exhibits the best impact resistance, while the cylindrical cutter with a 0.2 mm chamfer shows the poorest performance. According to the median FFE, the impact resistance of the 160 tri-ridged cutter with diamond mix #B is 5.3 times higher than that of the cylindrical cutter with a 0.2 mm chamfer.

According to Figs. 6, 8 and 12, the Ø19 mm 160 tri-ridged cutter with diamond mix #B demonstrated superior ROP enhancement potential and impact resistance, making it the optimal choice for the nose and shoulder areas of the bit in subsequent field trials in the Binnan region. A combination of axe-shaped and cylindrical cutters was selected for the cone area. Consequently, a Ø215.9 mm

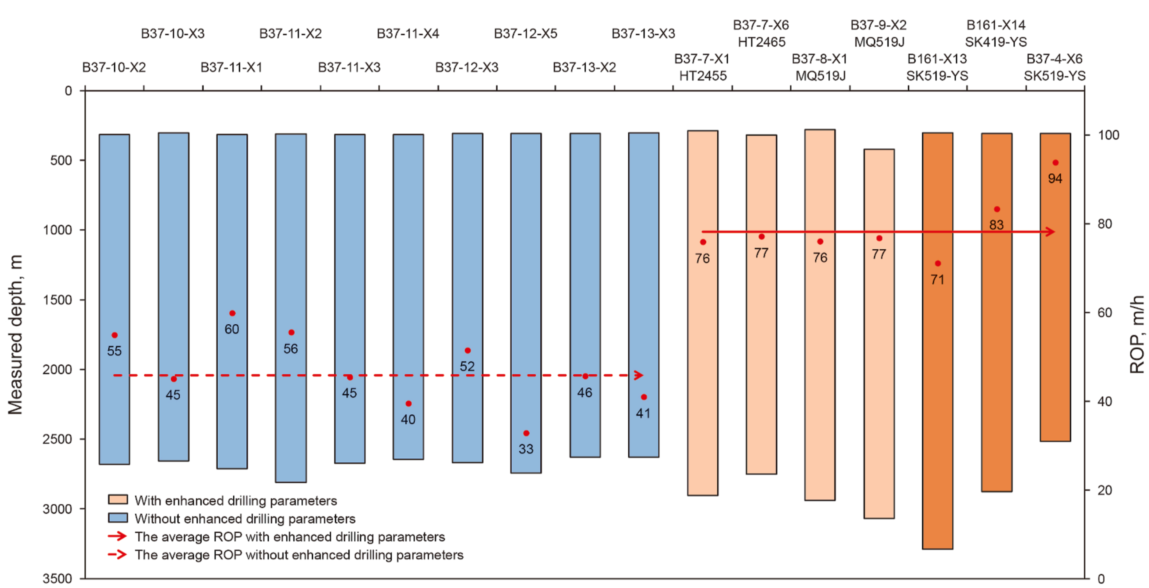

Fig. 10. Effect of enhanced drilling parameters on the ROP in Binnan region.

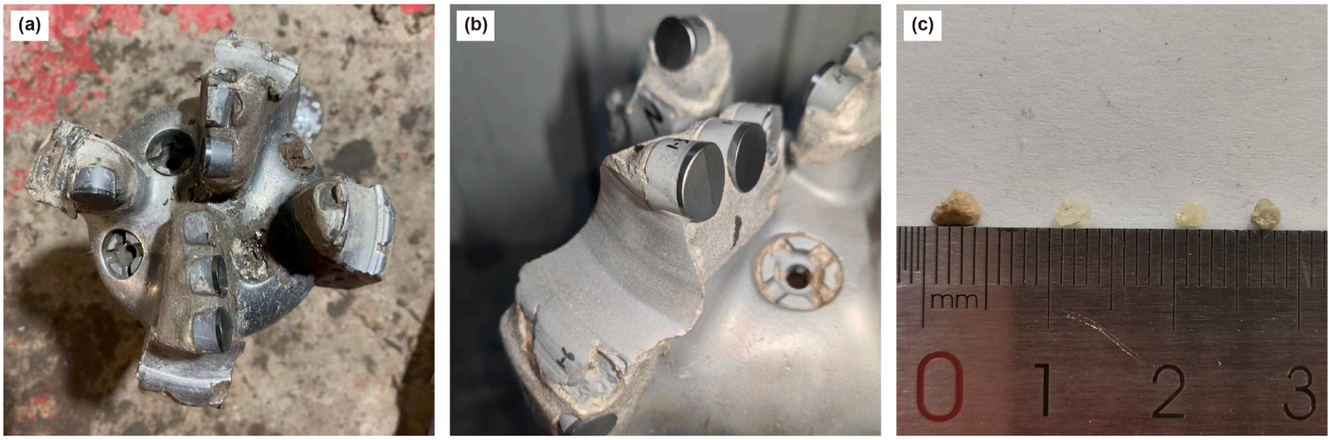

Fig. 11. (**a**, **b**) the bit with ring-out, (**c**) the gravel found in the Guantao Formation.

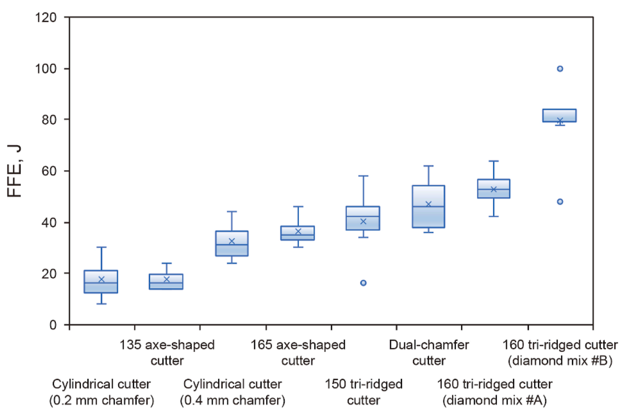

Fig. 12. The effects of cutter shape and PCD material properties on the impact resistance.

SK519-YS PDC bit was designed (Fig. 13(a)). The novel bit was field-tested in B161-X13 well located in the Binnan region, utilizing enhanced drilling parameters (Table 1), an Ø172 mm high-speed motor, two QDP-2600 mud pumps, and an XSL-225 top drive system. As illustrated in Fig. 13(b) and (c), the SK519-YS PDC bit remains in satisfactory dull conditions after the field run in the B161-X13 well, which drilled to the target depth in one run with a footage of 2986 m and a ROP of 71.1 m/h (Fig. 10).

4.2. Extended directional nozzles

Previous studies have shown that increasing hydraulic energy enhanced cuttings removal efficiency (Moslemi and Ahmadi, 2014) and the impact force of the jet, leading to greater rock erosion performance induced by the jet (Liu et al., 2015), thereby improving the ROP. In addition, aggressive hydraulic structure designs, such as increasing the height-to-width ratio of the blade and configuring a ballistic waterway profile, aim to increase the open face volume (OFV) and facilitate rapid evacuation of cuttings from the bottomhole and cutter surface into the annulus. However, increasing the height-to-width ratio of the blade extends the distance from the nozzle outlet to the bottomhole, which increases the energy dissipation of the drilling fluid jet.

The extended directional nozzle provides an effective solution for reducing jet dissipation and improving hydraulic energy utilization, without changing the bit's structural design. Fig. 14 illustrates a comparison between the traditional nozzle and the extended directional nozzle. The hydraulic performance of the novel nozzle, featuring a directional outlet structure, was analyzed through computational fluid dynamics (CFD) simulations (Feng et al., 2022). As shown in Fig. 15, the extended directional nozzle enhances the drilling fluid flow velocity around the cutters, increases the maximum wall shear stress on the cutter surface by 46.1%, reduces jet diffusion, and decreases the average erosion rate of the bit by 30.9%.

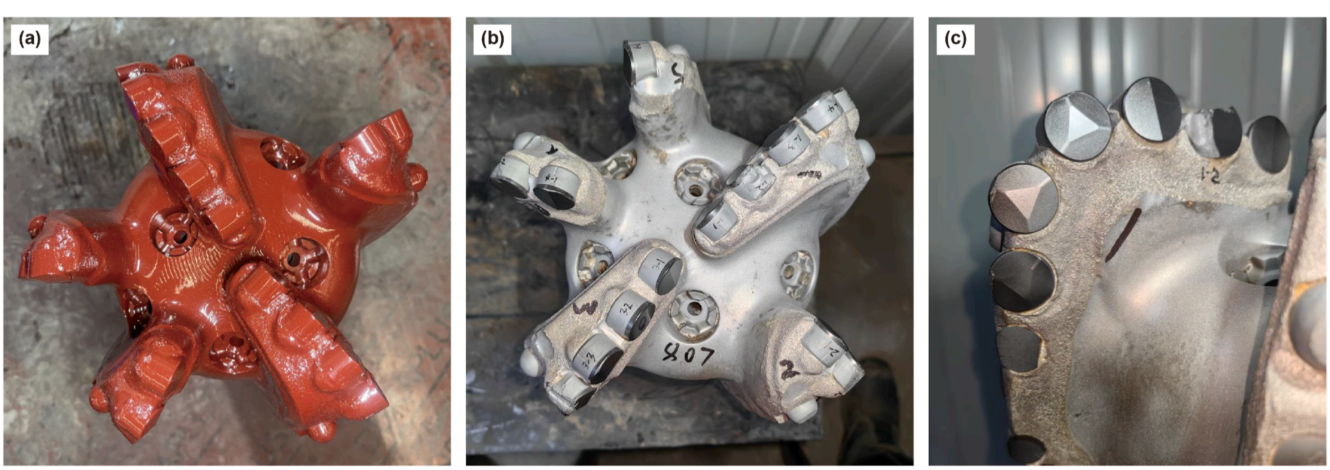

Fig. 13. (**a**) SK519-YS bit; (**b**, **c**) the SK519-YS bit remained in satisfactory dull conditions after field run.

Table 1
Enhanced drilling parameters in Binnan region.

	Well	Bit type	Nozzle type, mm	WOB, kN	Surface rotational rate, rpm	Flow rate, L/s	Pump pressure, MPa
Conventional parameters	/	/	/	40–80	60–90	≤ 30	17–18
Enhanced drilling parameters	B161-X13	SK519-YS	Ø8 × 5	80–120	90–120	30–38	20–28
	B161-X14	SK419-YS	Ø9 × 4	80–120	80–120	30–38	21–28
	B37-4-X6	SK519-YS	Ø7 × 4+ Ø8 × 1	80–120	100–110	32–36	20–28

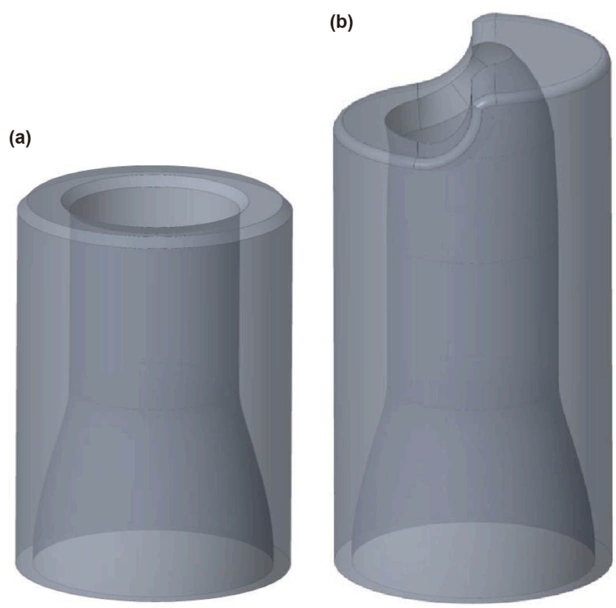

Fig. 14. **(a)** Traditional nozzle and **(b)** extended directional nozzle.

To further analyze the operating conditions of the extended directional nozzle, the jet impact performance of the extended directional nozzle was compared under different flow rates. As shown in Fig. 16(a) and (c), it is observed that at a lower flow rate of 25 L/s, the bottomhole pressure variation at the nozzle outlet is relatively small when altering from traditional nozzle to extended directional nozzles. However, as the flow rate increased from 25 to 38 L/s, Fig. 16(b) and (d) demonstrate a significant enhancement in bottomhole pressure. The bottomhole pressure at the nozzle outlet with the extended directional nozzle bit achieves a maximum improvement of 44.5% at 38 L/s compared to 25 L/s. This indicates that insufficient hydraulic energy results in limited jet impact performance, emphasizing the critical role of flow rate in achieving effective drilling.

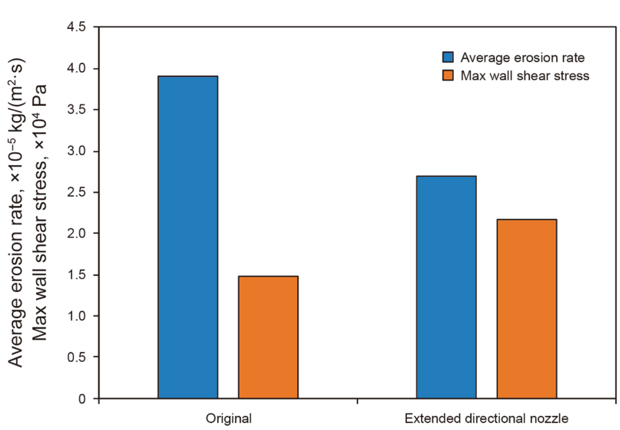

Fig. 15. Comparison of hydraulic performance of conventional nozzle and extended directional nozzle PDC bit.

The Ø19 mm 160 tri-ridged cutter with diamond mix #B and extended directional nozzles (Ø9 mm × 4) were adopted for the SK419-YS bit (Fig. 17(a)), which was tested in the B161-X14 well. A footage of 1930 m was achieved within the initial 24 h of drilling, representing an increase of 230–330 m compared to the conventional 24 h footage in the adjacent wells, which typically ranges from 1600 to 1700 m. As shown in Fig. 10, the footage and ROP of B161-X14 well reach 2571 m and 83.4 m/h, respectively, with the ROP exceeding that of the B161-X13 well by 17.3%. Fig. 17(b) and (c) show that three of the total four extended directional nozzles are broken after the field run. The fracture morphology suggests that the fractures are likely caused by lateral external forces, with the fracture direction oriented toward the well wall. The breakage is most likely attributed to directional drilling and the interbedded formation. Fig. 17(c) illustrates that fractures in all three nozzles occurred at the diameter transition step. Furthermore, an analysis of the erosion patterns on the threaded sleeves indicates that the fractures of the nozzles occur near the final stage of the drilling operation, but don't occur at different times. In addition, the breakage of the cemented tungsten carbide nozzles may have exerted further impacts on the cutters, contributing to the impact damage to the cutters (Fig. 17(b) and (d)).

Fig. 17(b) and (c) show that traditional extended directional nozzles are susceptible to structural failure. To protect the inner nozzle, an interference fit was employed between the inner and outer components, and the length of the externally threaded sleeve was extended. The optimized nozzle design is illustrated in Fig. 18(a), whose field test was conducted in the N19-X505 well in the adjacent Gudao region of Shengli Oilfield. The optimized extended directional nozzles (4 × Ø9 mm) were installed on the Ø241.3 mm SK419-YS bit (Fig. 18(b)), with the drilling interval ranging from 366 to 1436 m. The drilling parameters included a WOB of 30–60 kN, a surface rotational speed of 70–80 rpm, a flow rate of 26–30 L/s, and a pump pressure of 14–17 MPa. Fig. 18(c) shows that the nozzle structure remains intact after the field run. Since conventional drilling parameters were employed in this well, the bit's ROP was 32.42 m/h, which was comparable to that of adjacent wells on the same drilling platform. This result also demonstrated that the extended directional nozzle was less effective when used under traditional drilling parameters.

Then, the optimized extended directional nozzles (Ø7 mm × 4 + Ø8 mm × 1) were installed on the SK519-YS model PDC bit (Fig. 19(a)) and tested in the B37-4-X6 well. During the drilling of the B37-4-X6 well, the effect of flow rate on ROP was analyzed. Fig. 20 provides a profile comparison of formation, lithology and ROP of the B161-X14 and B37-4-X6 wells. As shown, when drilling at 2400–2490 m in the B37-4-X6 well, the drilling fluid pump stroke increased from 90 to 95 strokes per minute (SPM), resulting in a flow rate increase from 33.8 to 35.7 L/s. With the enhancement of hydraulic energy, the average ROP increased from 24.8 m/h (2300–2399 m) to 57.7 m/h (2400–2490 m), representing a significant increase in ROP.

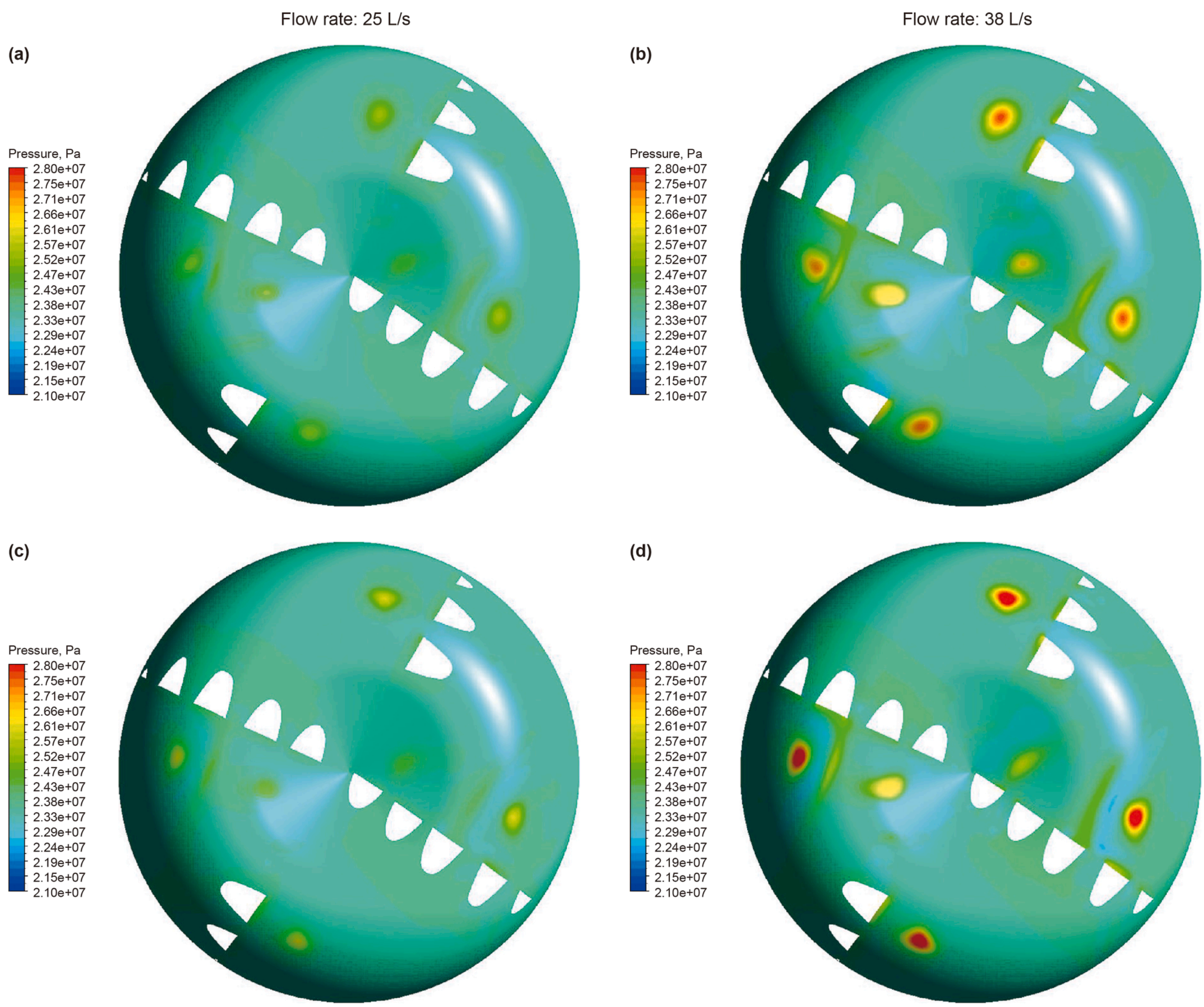

Fig. 16. The jet impact performance at various flow rates: (**a**, **b**) conventional nozzles; (**c**, **d**) extended directional nozzle.

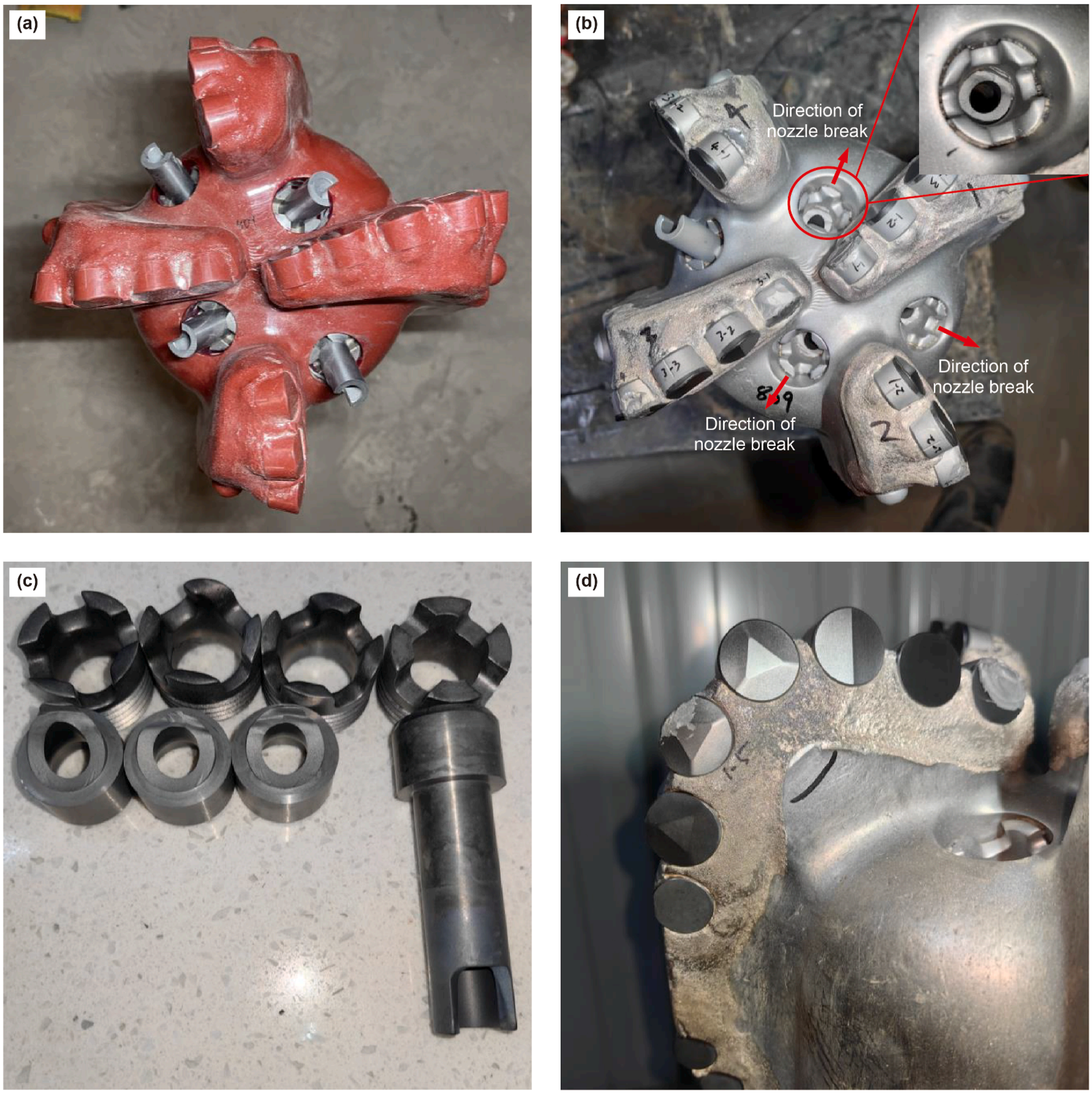

Fig. 17. **(a)** The SK419-YS bit deployed with the extend directional nozzles; **(b**, **c)** the extended directional nozzles were broken after the field run; and **(d)** damaged cutters on the shoulder and cone.

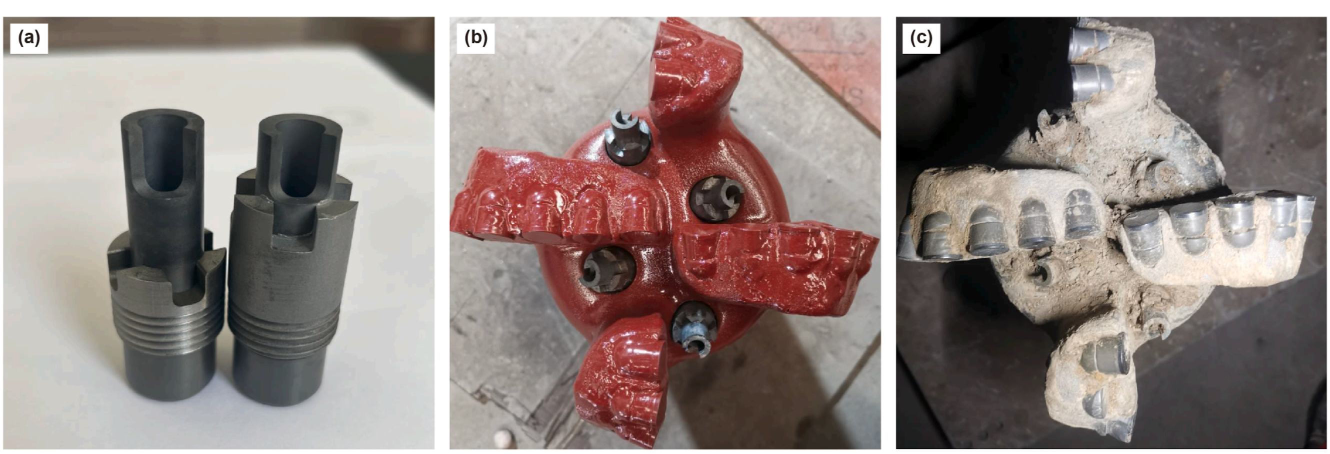

Fig. 18. **(a)** Comparison before and after the optimization of extended directional nozzles; **(b)** the SK419-YS bit with the optimized extended directional nozzles; **(c)** intact extended directional nozzles after the field run.

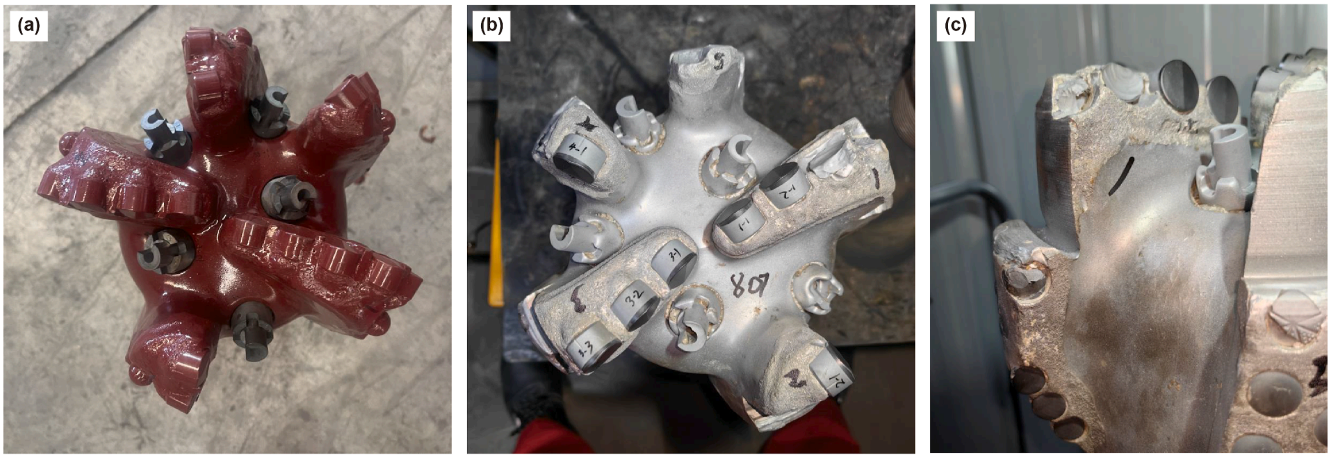

Fig. 19. **(a)** The SK519-YS bit with optimized extended directional nozzles; **(b, c)** the SK519-YS bit with ring-out after the field run.

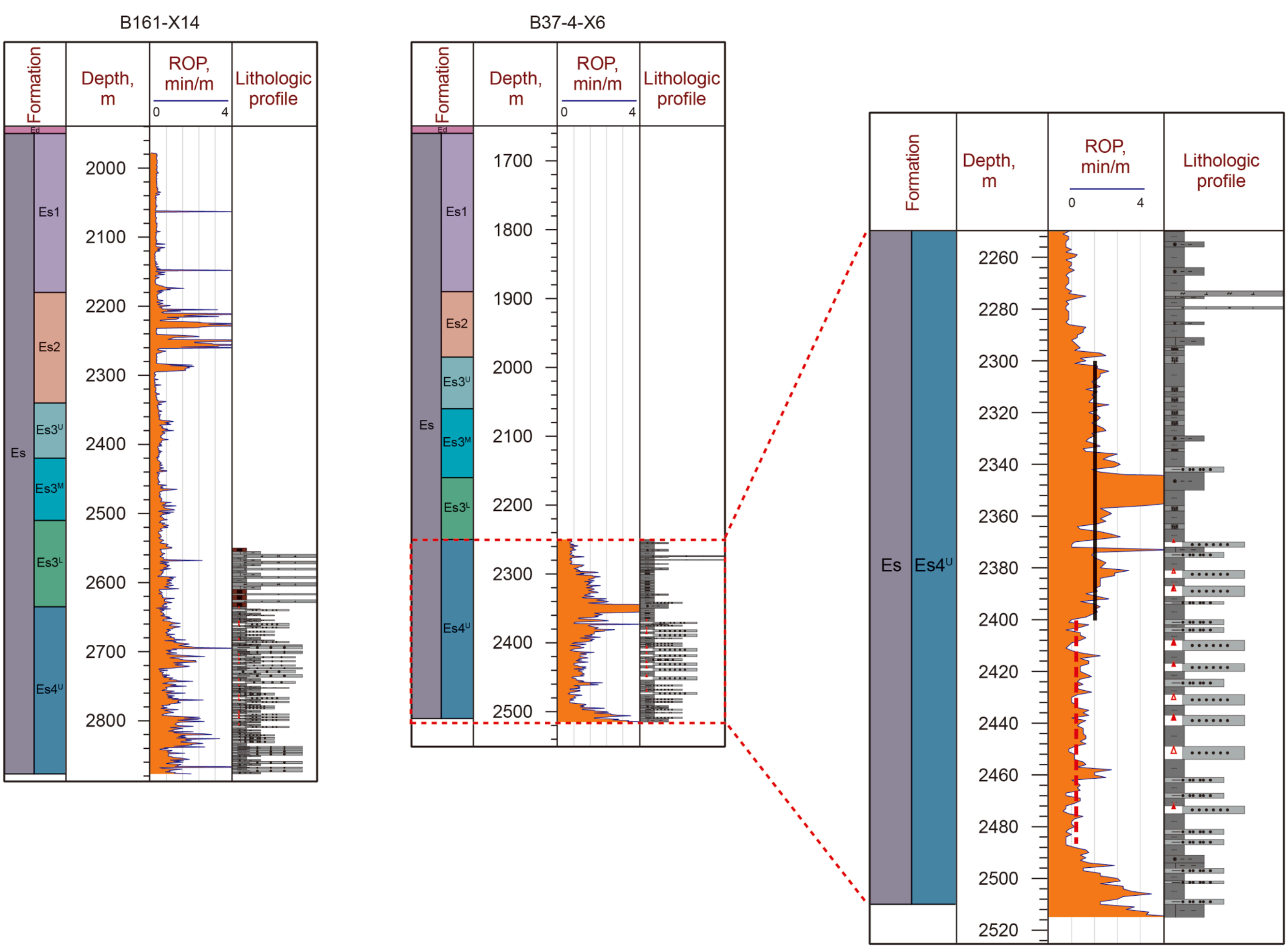

Fig. 20. Profile of formation, lithology and ROP of B161-X14 and B37-4-X6 wells.

The optimized extended directional nozzles, combined with the enhanced flow rate, enabled the ROP of the B37-4-X6 well to reach 93.91 m/h, representing a 32.1% improvement compared to the B161-X13 well, with a total footage of 2207 m (Fig. 10). According to Fig. 19, the structure of the optimized extended directional nozzle remained mostly intact after the field run, with only one out of five nozzles experiencing fracture. In addition, the shoulder area of the bit sustained significant damage and exhibited ring-out. This damage was attributed to the formation lithology, highlighting the need for further optimization of bit durability.

5. Conclusion

(1) The rock type exerted a significant impact on the ROP, followed by the drilling parameters, and then by the bit designs such as the cutter shape and size. For the target formations, the enhanced drilling parameters and optimized bit designs were effective methods to improve the bit's ROP.

(2) WOB was the primary limiting factor for increasing ROP in the relatively easy-to-drill formations. On the other hand, the torque became more and more important when the formations became increasingly hard-to-drill.

(3) In both the easy-to-drill and hard-to-drill formations, the effect of enhanced drilling parameters was significantly greater than the one of tailoring cutter size and shape. The larger cutter size such as Ø19 mm was more beneficial for improving ROP in relatively easy-to-drill formations, while smaller cutter size such as Ø16 mm was more conducive for hard-to-drill formations.

(4) The enhanced drilling parameters resulted in a significant increase in ROP, but also accelerated bit failure. Accordingly, the bit durability could be improved through the optimization of cutter shape and diamond table compositions. The tri-ridged cutter with the tough diamond mix exhibited the best impact resistance, making it the optimal choice for the bit's nose and shoulder areas and achieving one-trip drilling in the Binnan region.

(5) Extended directional nozzle was less effective under conventional hydraulic parameters but showed significant ROP improvements when aggressive hydraulic parameters were employed. In addition, the extended directional nozzle was susceptible to structural failure, which was solved by adopting an interference fit combined with extending the length of the externally threaded sleeve.

CRediT authorship contribution statement

Chao-Chao Feng: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Yong Li:** Conceptualization. **Wei Liu:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **De-Li Gao:** Supervision, Funding acquisition.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by Beijing Natural Science Foundation (Grant number: 2232060), the Ministry of Industry and Information Technology (Grant number: ZX20240310), and National Natural Science Foundation of China (Grant numbers: 52574016, 52394250, 52234002).

References

Azar, M., White, A., Velvaluri, S., et al., 2013. Middle east hard/abrasive formation challenge: reducing PDC cutter volume at bit center increases ROP/drilling efficiency. In: SPE/IADC Middle East Drilling Technology Conference & Exhibition. https://doi.org/10.2118/166755-MS.

Chen, X., Cao, T., Yu, K., et al., 2020. Numerical and experimental investigation on the depressurization capacity of a new type of depressure-dominated jet mill bit. Pet. Sci. 17, 1602–1615. https://doi.org/10.1007/s12182-020-00472-8.

Chen, X., Gao, D., Guo, B., 2016. A method for optimizing jet-mill-bit hydraulics in horizontal drilling. SPE J. 21 (2), 416–422. https://doi.org/10.2118/178436-PA.

Ciccu, R., Grosso, B., 2014. Improvement of disc cutter performance by water jet assistance. Rock Mech. Rock Eng. 47, 733–744. https://doi.org/10.1007/s00603-013-0433-4.

Doak, J., Kravits, M., Spartz, M., et al., 2018. Drilling extended laterals in the Marcellus Shale. In: SPE/AAPG Eastern Regional Meeting. https://doi.org/10.2118/191783-18ERM-MS.

Dupriest, F., Noynaert, S., 2022. Drilling practices and workflows for geothermal operations. In: IADC/SPE International Drilling Conference and Exhibition. https://doi.org/10.2118/208798-MS.

Dupriest, F., Koederitz, W., 2005. Maximizing drill rates with real-time surveillance of mechanical specific energy. In: SPE/IADC Drilling Conference. https://doi.org/10.2118/92194-MS.

Feng, C., Liu, W., Gao, D., 2022. CFD simulation and optimization of slurry erosion of PDC bits. Powder Technol. 408, 117658. https://doi.org/10.1016/j.powtec.2022.117658.

Gao, D., Liu, W., Wan, X., et al., 2023. Study on key factors influencing the ROP improvement of PDC bits. Petrol. Drill. Tech. 51 (4), 20–34. https://doi.org/10.11911/syztjs.2023022 (in Chinese).

Gao, M., Zhang, K., Zhou, Q., et al., 2020. Numerical investigations on the effect of ultra-high cutting speed on the cutting heat and rock-breaking performance of a single cutter. J. Pet. Sci. Eng. 190, 107120. https://doi.org/10.1016/j.petrol.2020.107120.

Gao, Y., Kong, L., Wang, Y., et al., 2024. Optimised design of downhole turbodrills with bending-torsional tilting blade. Geoenergy Sci. Eng. 234, 212661. https://doi.org/10.1016/j.geoen.2024.212661.

German, V., Pak, M., Azar, M., et al., 2015. Conical diamond element bit sets new performance benchmarks drilling extremely hard carbonate/chert formations, Perm region Russia. In: SPE/IADC Drilling Conference and Exhibition. https://doi.org/10.2118/173144-MS.

Gumich, D., Pak, M., Lomov, A., et al., 2017. New ridge diamond elements improve PDC bit efficiency. In: SPE Russian Petroleum Technology Conference. https://doi.org/10.2118/187717-MS.

He, Y., Wang, Y., Zhang, D., et al., 2021. Optimization design for turbodrill blades based on a twisting method. J. Pet. Sci. Eng. 205, 108892. https://doi.org/10.1016/j.petrol.2021.108892.

Izbinski, K., Cardoe, J., Bomidi, J., 2019. Increased ROP by 18% in Norway and in other applications through optimizing cutter geometry from laboratory tests, numerical models and field tests. In: SPE/IADC International Drilling Conference and Exhibition. https://doi.org/10.2118/194160-MS.

Judzis, A., Boucher, M., McCammon, J., et al., 2006. Investigation of smaller-footprint drilling system; ultrahigh-rotary-speed diamond drilling has potential for reduced energy requirements. In: IADC/SPE Drilling Conference. https://doi.org/10.2118/99020-MS.

Li, Y., Zhang, K., Wang, Y., et al., 2024a. Analysis of drilling response under ultra-high-speed diamond drilling: theory and experiment. Geoenergy Sci. Eng. 243, 213239. https://doi.org/10.1016/j.geoen.2024.213239.

Li, H., Li, J., Guo, C., et al., 2024b. Sandstone breaking performances and mechanisms of swirling abrasive waterjet during radial jet drilling process. Pet. Sci. 21 (6), 4298–4310. https://doi.org/10.1016/j.petsci.2024.05.028.

Li, J., Kuru, E., Li, W., et al., 2025. The flow field characteristics and rock breaking ability of cone-straight abrasive jet, rotary abrasive jet, and straight-rotating mixed abrasive jet. Pet. Sci. 22 (6), 2457–2464. https://doi.org/10.1016/j.petsci.2025.04.010.

Liao, H., Guan, Z., Shi, Y., et al., 2015. Field tests and applicability of downhole pressurized jet assisted drilling techniques. Int. J. Rock Mech. Min. Sci. 75, 140–146. https://doi.org/10.1016/j.ijrmms.2015.01.014.

Liu, S., Ni, H., Wang, X., et al., 2018. Rock-breaking mechanism study of axial and torsional impact hammer and its application in deep wells. In: IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition. https://doi.org/10.2118/191077-MS.

Liu, S., Zhou, F., Li, H., et al., 2020. Experimental investigation of hard rock breaking using a conical pick assisted by abrasive water jet. Rock Mech. Rock Eng. 53, 4221–4230. https://doi.org/10.1007/s00603-020-02168-2.

Liu, W., Gao, D., 2023. Research status and development trends of polycrystalline diamond compact bits. Sci. Technol. Foresinght 2 (2), 168–179. https://doi.org/10.3981/j.issn.2097-0781.2023.02.013 (in Chinese).

Liu, W., Li, Y., Gao, D., 2024. New understandings of the applications of PDC cutters in oil and gas drilling. Int. J. Refract. Met. Hard Mater. 122, 106724. https://doi.org/10.1016/j.ijrmhm.2024.106724.

Liu, W., Li, F., Zhang, J., et al., 2025a. Synthesis of polycrystalline diamond using C_{60} as binder for deep-earth scientific exploration. Adv. Compos. Hybrid Mater. 8, 299. https://doi.org/10.1007/s42114-025-01377-z.

Liu, W., Li, Y., Gao, D., et al., 2025b. Microstructure and properties of polycrystalline diamond with $AlCoCrFeNi_{2.1}$ eutectic high-entropy alloys as binder. Adv. Compos. Hybrid Mater. 8, 124. https://doi.org/10.1007/s42114-025-01214-3.

Liu, W., Dong, H., Wei, J., et al., 2025c. Optimizing the cutting efficiency of shaped polycrystalline diamond compact cutters by adjusting the cutter orientation. SPE J. 30 (4), 1680–1693. https://doi.org/10.2118/224405-PA.

Liu, W., Wei, J., Ge, Y., et al., 2025d. New prediction method for ROP potential of shaped PDC cutters. SPE J. 30 (4), 1670–1679. https://doi.org/10.2118/223969-PA.

Liu, X., Liu, S., Ji, H., 2015. Numerical research on rock breaking performance of water jet based on SPH. Powder Technol. 286, 181–192. https://doi.org/10.1016/j.powtec.2015.07.044.

Lu, J., Kong, L., Wang, Y., et al., 2024. Optimized parameters of downhole all-metal PDM based on genetic algorithm. Pet. Sci. 21 (4), 2663–2676. https://doi.org/10.1016/j.petsci.2024.03.022.

Meng, X., Zhou, H., Fan, H., et al., 2016. A systematic drilling hydraulics optimization method for improving rate of penetration and its application in ultra-deep wells. In: International Petroleum Technology Conference. https://doi.org/10.2523/IPTC-18829-MS.

Moslemi, A., Ahmadi, G., 2014. Study of the hydraulic performance of drill bits using a computational particle-tracking method. SPE Drill. Complet. 29 (1), 28–35. https://doi.org/10.2118/169812-PA.

Moslemi, A., Rahmani, R., Graham, R., et al., 2015. Hydraulic design of shale drill bit using an integrated numerical and experimental approach. In: SPE/IADC Drilling Conference and Exhibition. https://doi.org/10.2118/173038-MS.

Negm, S., Aguib, K., Karuppiah, V., et al., 2016. The disruptive concept of 3D cutters and hybrid bits in polycrystalline diamond compact drill-bit design. In: Abu Dhabi International Petroleum Exhibition & Conference. https://doi.org/10.2118/183335-MS.

Ochoa, D., Palacio, J., Akinniranye, G., et al., 2009. A fit for purpose combination of positive displacement motor and rotary steerable systems delivers a step change in drilling optimization in Tomoporo field: a west Venezuela case study. In: SPE/IADC Drilling Conference and Exhibition. https://doi.org/10.2118/119428-MS.

Pak, M., Azar, M., Bits, S., et al., 2016. Conical diamond element enables PDC bit to efficiently drill chert interval at high ROP replacing turbine/impregnated BHA. In: IADC/SPE Drilling Conference and Exhibition. https://doi.org/10.2118/178765-MS.

Rahmani, R., 2019. Rock customized shaped cutters improve rock cutting efficiency. In: SPE/IADC International Drilling Conference and Exhibition. https://doi.org/10.2118/194148-MS.

Rahmani, R., Bradford, J., Barocio, H., 2016. New drill bit technology sets drilling records in carbonates and harsh rock applications. In: Abu Dhabi International Petroleum Exhibition & Conference. https://doi.org/10.2118/183397-MS.

Samuel, G.R., Miska, S., 2000. Theoretical analysis and design modification of PDM for air drilling. SPE/ICoTA Coiled Tubing Roundtable. https://doi.org/10.2118/60710-MS.

Schnuriger, M., Cuillier, B., Tilleman, D., et al., 2017. Curved nozzle design for PDC bits enhances hydraulics for bit cleaning and cooling improvements. In: SPE/IADC Drilling Conference and Exhibition. https://doi.org/10.2118/184734-MS.

Shamea, N., Suleiman, A., Bailey, M.J., et al., 2020. Demonstrating reliability, improved efficiency and robustness whilst deploying novel shaped PDC cutter geometries. In: Abu Dhabi International Petroleum Exhibition & Conference. https://doi.org/10.2118/202929-MS.

Shao, F., Liu, W., Gao, D., et al., 2021. Study on rock-breaking mechanism of axe-shaped PDC cutter. J. Pet. Sci. Eng. 205, 108922. https://doi.org/10.1016/j.petrol.2021.108922.

Staley, C., Bruton, G., Natanael, M., et al., 2011. Turbodrill BHA solves build section challenges, Anadarko Basin. In: SPE/IADC Drilling Conference and Exhibition. https://doi.org/10.2118/140245-MS.

Walker, B.H., Black, A.D., Klauber, W.P., et al., 1986. Roller-bit penetration rate response as a function of rock properties and well depth. In: SPE Annual Technical Conference and Exhibition. https://doi.org/10.2118/15620-MS.

Wang, H., Huang, H., Bi, W., et al., 2022. Deep and ultra-deep oil and gas well drilling technologies: progress and prospect. Nat. Gas. Ind. B 9 (2), 141–157. https://doi.org/10.1016/j.ngib.2021.08.019.

Wang, H., Liao, H., Wei, J., et al., 2023. Stress release mechanism of deep bottom hole rock by ultra-high-pressure water jet slotting. Pet. Sci. 20 (3), 1828–1842. https://doi.org/10.1016/j.petsci.2022.12.002.

Wells, M., Marvel, T., Beuershausen, C., 2008. Bit balling mitigation in PDC bit design. In: IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition. https://doi.org/10.2118/114673-MS.

Xi, Y., Wang, H., Zha, C., et al., 2023. Numerical simulation of rock-breaking and influence laws of dynamic load parameters during axial-torsional coupled impact drilling with a single PDC cutter. Pet. Sci. 20 (3), 1806–1827. https://doi.org/10.1016/j.petsci.2023.01.009.

Xu, Z., Jin, Y., Hou, B., et al., 2016. Rock breaking model under dynamic load with the application of torsional and axial percussion hammer. In: International Petroleum Technology Conference. https://doi.org/10.2523/IPTC-18777-MS.

Yuan, G., Fu, L., Wang, Y., et al., 2022. The up-to-date drilling and completion technologies for economic and effective development of unconventional oil & gas and suggestions for further improvements. Petrol. Drill. Tech. 50 (1), 1–12. https://doi.org/10.11911/syztjs.2022002 (in Chinese).