International Journal of Engineering Sciences and Technologies

Int. J. Eng. Sci. Technol.
2025.3(3).2
ISSN: 2958-2857
https://doi.org/10.58531/ijest/3/3/2

Article

Research and Application of Safe and Rapid Drilling Technology for Ultra-Deep Wells in Northwestern Sichuan

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Abstract: Ultra-deep well drilling in the Zhebachang Structure and Suining-Santai Qixia Formation Slope Structural Belt of northwestern Sichuan is confronted with a harsh environment characterized by high temperature, high pressure, and high stress. The geological conditions are complex, variable, and difficult to predict accurately. In the early drilling stage, widespread challenges were encountered, including the limited adaptability of existing drilling technologies, low drilling efficiency, and extremely high operational risks. Specifically, the regional ultra-deep wells suffered from a long drilling cycle (average 487 days), low rate of penetration (ROP, 2.35 m/h), and high complexity rate (14.21%).To address these issues, systematic research was conducted on engineering geomechanics, bottom hole assembly (BHA) optimization, drilling fluid system innovation, and parameter enhancement, which initially resolved the regional drilling technical bottlenecks and yielded four key insights:Innovative application of a bi-diameter bit (pilot hole Ø95–110 mm + reaming hole Ø455 mm) combined with a high-torque positive displacement motor (PDM, Ø286 mm) increased the specific water power by 25%. For the Φ455 mm wellbore, the ROP reached 4.05 m/h, representing a 52.83% improvement.Optimized trajectory control technology: A double-stabilizer pendulum BHA (Φ448–452 mm spiral stabilizer + Φ448–450 mm spiral stabilizer) was designed, integrated with an eccentric stabilizer. The well deviation was controlled within 0.15°–0.42°, a 60% reduction compared to adjacent wells.Narrow density window control technology was developed based on managed pressure drilling (MPD) and dual-density technology. This solved the safety density window challenge (≤0.05 g/cm³) in the Xujiahe Formation (pressure coefficient 2.37) and Jialingjiang Formation (coexisting lost circulation and well kick), reducing the complexity rate to 6.36%.Two high-performance drilling fluid systems were developed: (1) a "three-

Citation:Gao L. Research and Application of Safe and Rapid Drilling Technology for Ultra-Deep Wells in Northwestern Sichuan. *Int. J. Eng. Sci. Technol.*, 2025, 3(3), doi: 10.58531/ijest/3/3/2

low" water-based drilling fluid (low permeability, low activity, wettability reversal) and (2) a high-sealing oil-based drilling fluid (rigid-flexible particle gradation). Both systems withstand temperatures up to 200°C and show a 40% improvement in contamination resistance.Field trials verified the effectiveness of these technologies: the average ROP increased by 17.45%, the drilling cycle shortened by 12.26%, and the failure/complexity rate decreased by 55.24%.

Keywords: ultra-deep well; large-diameter wellbore; bi-diameter bit; managed pressure drilling (MPD) ; narrow density window; Northwestern Sichuan

1. Introduction

In the Zhebachang Structure and Suining-Santai Qixia Formation Slope Zone in Northwestern Sichuan, the burial depth exceeds 6000 meters, posing challenges such as high temperature (188℃), high pressure (pressure coefficient of 2.37), high stress, and the coexistence of multiple pressure systems. Statistics show that the average accident and complexity rate of 14 adjacent wells in this area reaches 14.21%, which seriously restricts exploration efficiency (Figure 1) [1]. Based on the actual drilling data of Well ZT1 and Well ST1, combined with rock mechanics experiments and drill string dynamics simulations, this paper proposes a set of safe and efficient drilling technology systems, providing a reference for similar ultra-deep well operations.

Table 1

Well	TD (m)	Formation	Drilling time (d)	Average ROP (m/h)
Guanji well	7175	Maokou	1083	0.97
Jiange 1	7728	Qixia	444.93	2.74
Chuanshen 1	8420	Dengying-4	549	2.08
Jiaotan 1	7766	Dengying-3	427.77	2.33
Pengshen 6	9026	Dengying-2	561.31	3.34
Pengshen 2	7930	Dengying-4	664.25	2.60
Pengshen 7	7516	Dengying-4	441.75	2.95
Pengshen 9	7275	Dengying-3	439.42	2.68
Santai 1	6920	Liangshan	293	4.09

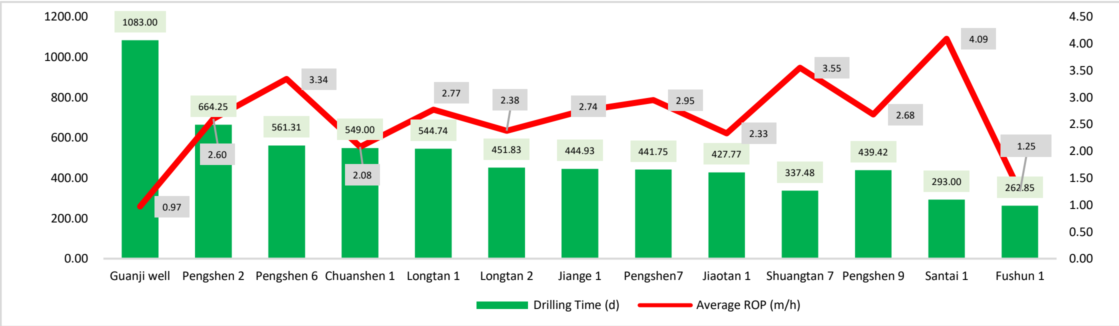


Figure 1 Statistics on Drilling Time and Rate of Penetration (ROP) of Offset Wells in Northwestern Sichuan

2. Analysis of Engineering Geology Difficulties

2.1 Formation Characteristics and Risks

2.1.1 Low Drilling Efficiency of large-Size Wellbores

Wellbores with a diameter of Φ455 mm or larger encounter the interbedded sandstone and mudstone of the Shaximiao Formation – Ziliujing Formation, where the rock uniaxial compressive strength (UCS) ranges from 35 to 150 MPa and the abrasiveness index is ≥6 [2]. The rheological properties of high-density drilling fluid (1.53 g/cm³) deteriorate, leading to a cuttings carrying efficiency of less than 60%; meanwhile, the thick virtual mud cake on the wellbore wall causes frequent sticking incidents (the sand settling in Well PS6 reached 21.8 m). For large-size wellbores, when using high-density drilling fluid, poor rheological properties result in inadequate wellbore wall scouring effect, which easily forms a thick virtual mud cake on the wellbore wall. This causes wellbore blockage and hinders the improvement of drilling speed. The Ziliujing Formation interval is a plastic formation with interbedded sandstone and mudstone; under the compaction effect of high-density drilling fluid, the rate of penetration (ROP) of Well PS2 in this interval was only 1.17 m/h.

2.1.2 Low Rate of Penetration (ROP) in Hard-to-drill Formations

The Xujiahe Formation consists of interbedded sandstone and shale, locally gravel-bearing, with a silica content of 25%. A total of 10 drill bits were used in the Xujiahe Formation of Well Jiaotan 1, with an average rate of penetration (ROP) of only 1.49 m/h. The Maokou Formation – Qixia Formation has well-developed chert bands, making it easy to encounter high-silica limestone formations; alternatively, when drilling into the tight sandstone formations of the Canglangpu Formation (Cambrian System), the drillability grade ranges from 7 to 8 [3], and the actual average ROP is less than 2 m/h in both cases.The Wujiaping Formation has a burial depth of over 6000 m and a thickness of 150 m, mainly composed of siliceous limestone with chert and pyrite bands. It is characterized by low footage per single drill bit and extremely poor drillability, with an average ROP of only 0.99 m/h. Some wells encountered the Jinbaoshi Formation: the ROP of Well ST3 and Well ST8 was 0.42 m/h, and the drillability grade reached 8–10.

Table 2 ST3 well Drill Bits' situation of application in Wujiaping Formation

OD （mm）	**Bit Type**	**Bit Model**	**Drilling Section（m）**	**Formation**	**Footage （m）**	**ROP （m/h）**
241.3	PDC	WS566BEH	6970.86－6984.13	Wujiaping	13.27	0.65
241.3	Tricone	PC2	6984.13－7008.26	Wujiaping	24.13	1.34
241.3	PDC	MM65RH	7008.26－7027.54	Wujiaping	19.28	1.07
241.3	Tricone	HJ617GL	7027.54－7058.23	Wujiaping	30.69	0.86
241.3	Tricone	HJ617GL	7058.23－7094.59	Wujiaping	36.36	1.10

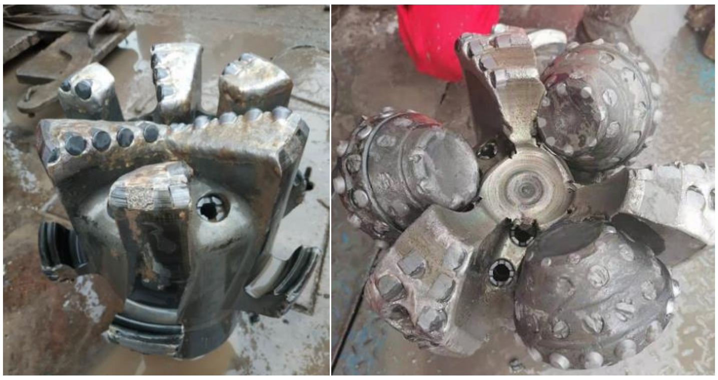


Figure 2 Drill bit bearing & coring

2.1.3 Safety Risks in Narrow Mud Weight Windows

There are three sets of pressure systems vertically:

(1) The Xujiahe Formation has high pressure (pressure coefficient: 2.15–2.37), and lost circulation occurred in multiple wells after well killing with high-density drilling fluid;

(2) The Leikoupo Formation–Jialingjiang Formation has low pressure (pressure coefficient: 1.85). Since the Xujiahe Formation (with abnormal high pressure) and the Leikoupo-Jialingjiang Formation are drilled in the same section (combined drilling), the risk of gas leakage is high;

(3) The Maokou Formation–Qixia Formation features the coexistence of lost circulation and fluid influx, with an extremely narrow safe drilling density window (safety window ≤ 0.05 g/cm³).

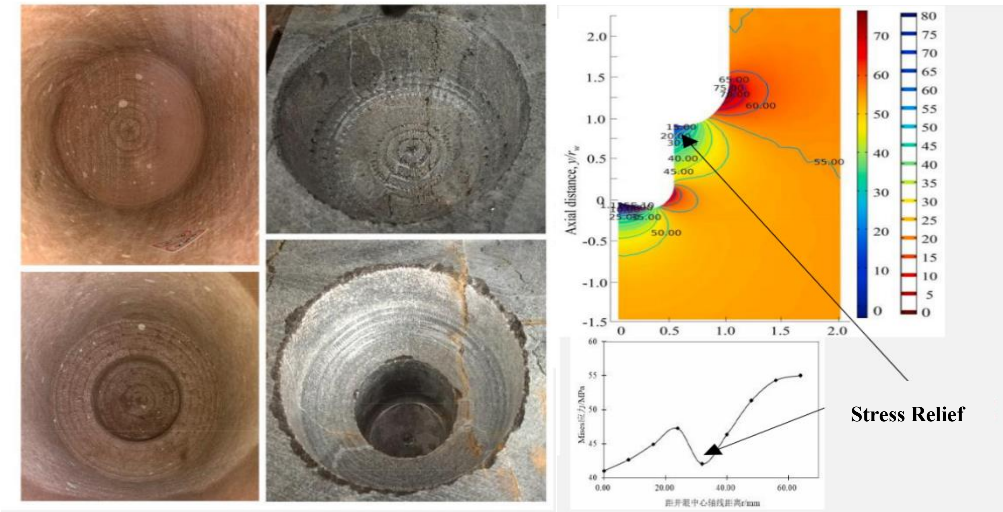
(4) High Temperature, High Pressure, and High Sulfur Content (HTHP-H_2S) Pose Significant Challenges to Working Fluids and Downhole Tools/Instruments

The reservoir burial depth exceeds 7000 meters. The maximum bottomhole temperature (BHT) of key reference wells in the region reaches 172℃; the predicted BHT of Well Zhetan 1 is approximately 188℃, and the predicted maximum formation pressure of the Qiongzhusi Formation is 164.19 MPa. For Well Suitan 1, the predicted BHT is around 165℃, with an expected maximum formation pressure of 140.18 MPa.According to the geological design of Well Zhetan 1, the H_2S content is predicted to be 22.5–44.24 g/m³ in the Leikoupo Formation, 0.047–43.12 g/m³ in the Feixianguan Formation, 1.16–25.94 g/m³ in the Maokou Formation, and 4.85–25.36 g/m³ in the Qixia Formation. For Well Suitan 1, the geological design predicts an H_2S content of 22.5–44.24 g/m³ in the Leikoupo Formation, 1.16–25.94 g/m³ in the Maokou Formation, and 4.85–25.36 g/m³ in the Qixia Formation.Some formations in the region have high sulfur content, and the existing high-temperature and oil-resistant positive displacement motor(PDM), logging tools, and wellbore Drilling fluids cannot fully meet the requirements for safe and efficient operations.

3 Key Technologies for Deep Earth Drilling

3.1 Drill Bit Technology for ROP Enhancement in Large-Size Wellbores

In Ø455 mm wellbores, the specific rock-breaking energy ratio of traditional polycrystalline diamond compact (PDC) bits reaches 3.5 kJ/cm³, imposing high requirements on the bit's wear resistance and impact resistance. By adopting a dual-diameter bit with two stages of different diameters, the equivalent stress unloading efficiency is improved, which is conducive to enhancing the overall drilling efficiency. Among them, the reaming section exhibits the characteristic of a secondary stress field with low radial stress and high circumferential stress, which significantly reduces the overall damage probability of the bit and gives full play to the rock-breaking advantages of PDC bits. Through pilot hole prebreaking (Ø95–110 mm), the dual-diameter bit reduces the confining pressure, leading to a 40% decrease in the rock-breaking stress of the reaming section (Figure 3) [5]. Compared with traditional PDC bits, the total effective stress on the dual-diameter bit is reduced by 15%–20%.



During the test of the SD6645SJ dual-diameter bit (Figure 4) in the Shaximiao-1 Formation of Well Zhetan 1, the bit was operated with a weight on bit (WOB) of 18–24 tonnes and a rotational speed of 70 rpm. The achieved rate of penetration (ROP) was 3.52 m/h, representing an increase of 69.12% compared with offset wells

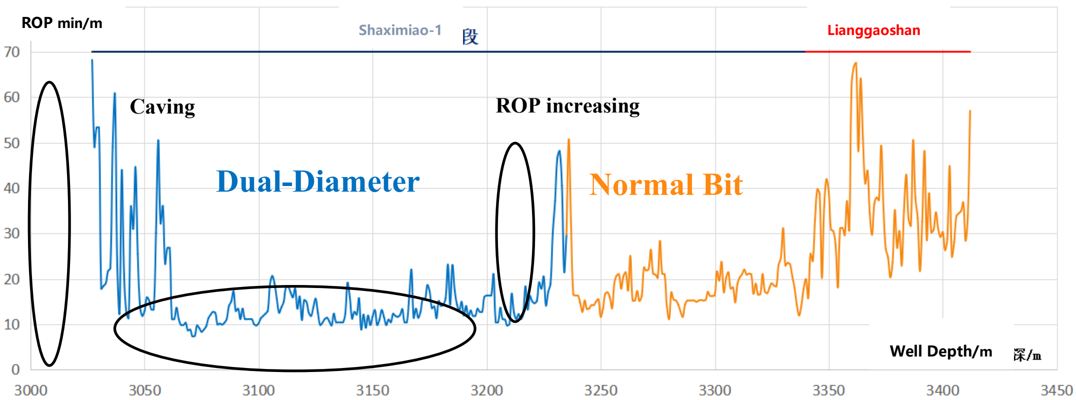


Figure 4 Comparison of Drilling ROP between Dual-Diameter and GS1606T Drill Bit

3.2 ROP Enhancement for Hard-to-Drill Formations in the Mid-Deep Section

3.2.1 Optimal Selection of High-Efficiency Drill Bits

In the Xujiahe, Maokou–Qixia, and Canglangpu Formation in northwestern Sichuan, the formations exhibit extremely high abrasiveness due to high contents of gravel, siliceous limestone, and quartz, resulting in an average rate of penetration (ROP) of less than 2 m/h.

Cuttings from 13 wells in the Penglai Gas Field were collected, and rock abrasiveness experiments were conducted on four sets of hard-to-drill formations, including the Xujiahe, Maokou, Qixia and Canglangpu Formation. The experimental results are shown in Table 3.

Table 3 Experimental Results of Rock Abrasiveness

NO.	Formation	Abrasiveness	Formation Drillability Classification
1	Xujiahe	27.6524	Medium
2	Xujiahe	47.1538	Relatively High
3	Xujiahe	34.7162	Above Medium
4	Qixia	14.9089	Below Medium
5	Canglangpu	37.3752	Above Medium
6	Canglangpu	48.1184	Relatively High

On this basis, the calculation model for the formation rock abrasiveness in the study area was optimized and determined, as shown in the figure 5 below.

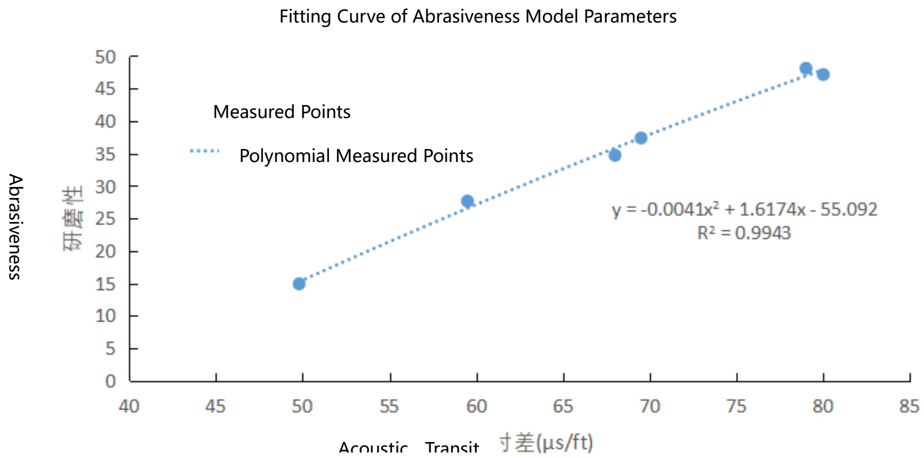


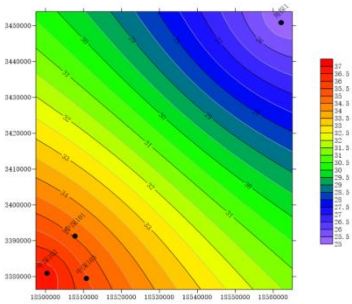
Figure 5 Fitting Results of Abrasiveness Model Parameters

$$w = -0.0041 \times \Delta t^2 + 1.62 \times \Delta t - 55$$

In the formula，W—Relative index of rock abrasiveness, unit: mg/cm³;

Δt —Acoustic transit time, $\mu s / \mathrm{ft}$ 。

Based on the model fitting results, maps of the lateral variation patterns of abrasiveness in the hard-to-drill formations of the Xujiahe Formation, Maokoun-Qixia Formation, and Canglangpu Formation were plotted, as shown in Figures 6 to 9.



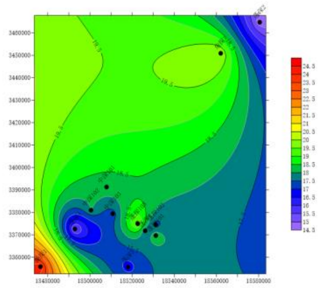
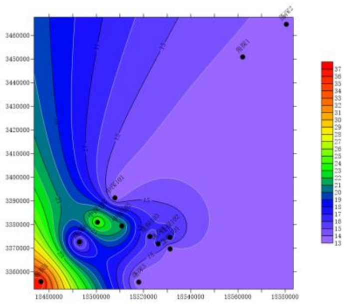


Figure 6 Lateral Profile of Abrasiveness of Xujiahe Formation

Figure 7 Lateral Profile of Abrasiveness of Maokou Formation



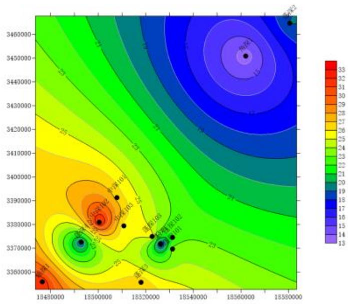


Figure 8 Lateral Profile of Abrasiveness of Qixia Formation

Figure 9 Lateral Profile of Abrasiveness of Canglangpu Formation

From the positional relationship of each well, combined with the lateral profiles of formation abrasiveness, it can be observed that: regionally, the Xujiahe Formation has extremely high abrasiveness; Well Suitan 1 has relatively high abrasiveness in the Maokou Formation; Well Zhetan 1 has moderate abrasiveness in the Maokou Formation and the Qixia Formation also has moderate abrasiveness; the Canglangpu Formation has extremely high abrasiveness, and the closer to Well Jiaotan 1, the lower the abrasiveness of the Canglangpu Formation.

Using scientific statistical methods, a scientific drill bit evaluation method was established. Based on the big data-based drill bit performance evaluation mechanism, drill bit selection charts for each formation were developed using the golden section optimization line, as shown in Figure 10. These charts provide guidance for drill bit selection in hard-to-drill formations.

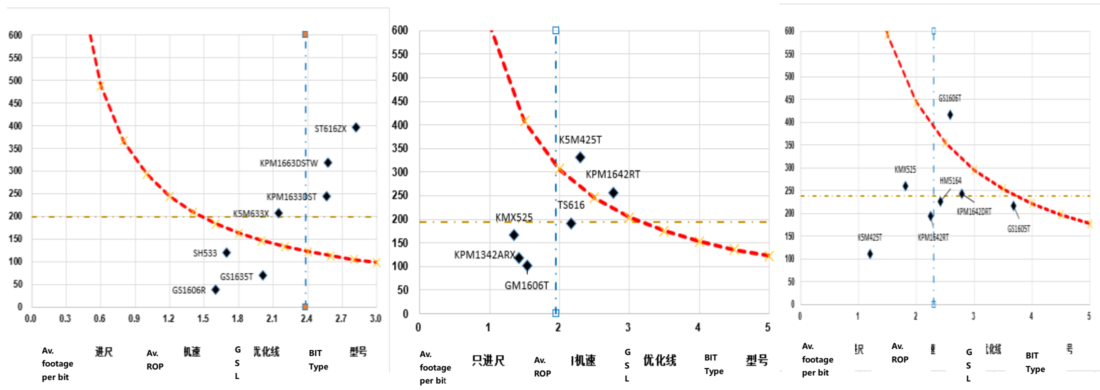


Figure 10 Golden Section Diagram of Drill Bits for Xujiahe Formation, Maokou Formation and Canglangpu Formation

Based on laboratory research on rock abrasiveness, combined with the analysis of regional hard-to-drill formations and their rock abrasiveness, a drill bit selection and optimized design scheme has been developed for the hard-to-drill formations of the Xujiahe , Maokou , Qixia and Canglangpu Formation.

The Xujiahe Formation has extremely high rock abrasiveness, so highly abrasion-resistant drill bits are preferred, such as 7-blade polycrystalline diamond compact (PDC) bits with 16 mm cutters (e.g., STR716ZX, DD507TX). The Maokou–Qixia Formation has moderate rock abrasiveness; 6-blade PDC bits with 16 mm cutters (e.g., GS1606T, STR616ZX) or 16 mm hybrid bits (e.g., KPM1642DRT, K5M633X) can be used. The Canglangpu Formation has extremely high rock abrasiveness and a relatively deep burial depth, so highly abrasion-resistant drill bits suitable for deep formations are preferred, such as Haiborui 6/7-blade PDC bits with 16 mm cutters (e.g., STR616ZX, STR716ZX).

Table 4 Optimal Drill Bit Selection Scheme for Hard-to-Drill Formations

Formation	Formation Abrasiveness	Drill Bit Recommendation
Xujiahe	Extremely high	ST616ZX、STR716ZX、KPM1663DSTW、KPM1633DST
Maokou～Qixia	Moderate	GS1606T、STR616ZX、KPM1642DRT、K5M633X
Canglangpu	Extremely high and relatively great burial depth	STR616ZX、STR716ZX

3.2.2 Optimal Selection of New-Type ROP-Enhancing Tools

(1) High-Speed Turbodrills

A high-speed turbodrill is a downhole power machine that converts the kinetic energy of drilling fluid into mechanical energy. It utilizes hundreds of stator-rotor turbine stages (made of cast steel or nylon, with opposite blade curvature directions) connected in series to transform the kinetic energy of drilling fluid into mechanical energy. This system is supplemented by thrust bearings and intermediate bearings to bear loads. During coring operations, it must be connected to core barrels. The core performance parameters of high-speed turbodrills include torque, rotational speed, and output power.

(2) Hydraulic Oscillators

The main structure of a hydraulic oscillator is composed of oscillation components, pressure sensing components, power components, and moving/static valve bodies. Hydraulic oscillators are used to address downhole drag (especially in horizontal wells/extended-reach wells). As shown in Figure 13, the main body includes oscillation, pressure sensing, power, and moving/static valve body components. A drilling fluid-driven motor causes the rotary valve to periodically vary the fluid impact pressure, which is then converted into the tool's oscillating force.

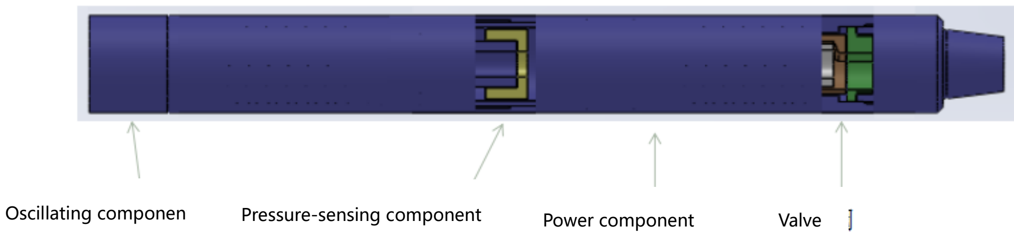


Figure 11 Main Structure of the Hydraulic Oscillator

(3) High-Torque positive displacement motor(PDM)

High-torque PDMs adopt equal wall thickness technology, where the rubber maintains a uniform thickness at both the wave crests and troughs inside the stator housing. This design allows the helical profile on the inner surface of the stator bushing to intermesh with the rotor, thereby achieving superior sealing performance and delivering twice the torque of conventional PDMs. As the torque capacity increases, the bit's output rotational speed remains constant, which in turn improves the rate of penetration (ROP).

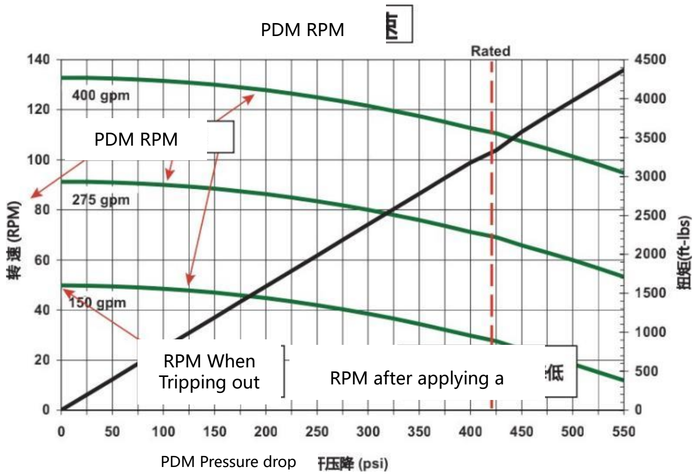


Figure 12 Performance Curve of High-Torque PDM

(4) Heavy-Duty Shock Absorbers

Heavy-duty shock absorbers are made of special high-quality alloy steel (4330V). Their service life is 4–5 times that of hydraulic shock absorbers, and their tensile strength and torsional strength are also higher than those of hydraulic shock absorbers. Additionally, their shock absorption effect is more significant than that of hydraulic shock absorbers.

3.3 Drill String Assembly Optimization

3.3.1 Optimization of Stabilizer Placement Position

Optimizing the placement position of stabilizers, The reasonable placement height of the stabilizer in the four-in-one drill string assembly directly affects the deviation prevention and deviation reduction effects of this drill string assembly. Calculation of the reasonable placement position of the stabilizer:

$$\mathrm{f1(x) = f2(x) + f3(x) + f4(x)}$$

Among them:

f1(x)—Deflection at position x caused by the couple M acting at the centralizer，m；

f2(x)—Deflection at position x caused by the uniformly distributed load q，m；

f3(x)—Rigid body displacement at position x caused by the movement of the centralize，m。

The calculations of f1(x)、f2(x) and f3(x) are as follows：

$$f1(x) = \frac{-M}{EIk^2}\left(\frac{x}{L} + \cos kx - ctgkL \cdot \sin kx - 1\right)$$

$$f2(x)=\frac{-q}{EIk^4}\left(\frac{\cos\left(kx-\frac{kL}{2}\right)}{\cos\frac{kL}{2}}-1-\frac{k^2L}{2}\left(x-\frac{x^2}{L}\right)\right)$$

$$f3(x)=-\frac{e\cdot x}{L}$$

In the formula：

L—Installation height of the centralizer，m；

e— Clearance between the centralizer and the wellbore wall,m；

$k=\frac{2u}{L}$，Calculation coefficient，m-1；

$u=\frac{L}{2}\sqrt{\frac{P}{EI}}$，Stability coefficient of the column, dimensionless；

EI—Stiffness of the drill collar，N.m2；

M—Bending moment at the centralizer，N.m；

q— Uniformly distributed load，N/m；

x—Distance from the drill bit to the centralizer，m。

3.3.2 Optimization of Drill String Assembly for Large-Diameter Wellbores

Considering the requirement of deviation prevention, the drill string assembly for the Φ455mm wellbore has been optimized from a single-stabilizer pendulum type to a double-stabilizer pendulum type. The size of the bottom drill collar has been upgraded from 9” to 11”, and extra-high torque PDM have been widely promoted and applied. Specifically, the torque of the Φ286mm PDM has been increased from 32,500 N·m to 46,000 N·m, and the size of the stabilizer has been expanded from Φ442mm to Φ450mm. This optimization not only enhances the fulcrum effect but also facilitates wellbore conditioning.In Well Zhetan-1 and Well Sui tan-1, the average well deviation of the Φ455mm wellbores is 0.15° and 0.42° respectively, which is better controlled compared with the average well deviation of 0.56° in adjacent wells.

Original Drill String Assembly:Φ455mm drill bit + Φ286mm straight PDM + drill string check valve + Φ228.6mm non-magnetic DC + Φ228.6mm DC + Φ440-442mm spiral stabilizer + Φ228.6mm DC + Φ203.2mm DC + Φ203.2mm drilling jar + Φ139.7mm HWDP + Φ139.7mm DP.

Optimized Drill String Assembly:Φ455mm drill bit + Φ286mm straight PDM + drill string check valve + Φ229mm shock absorber + 1×jt Φ279.4mm DC + Φ448~450mm spiral stabilizer + 1×jt Φ254mm DC + Φ448~450mm spiral stabilizer + deviation measuring sub + 6×jts Φ228.6mm DC + 6×jts Φ203.2mm DC + Φ203.2mm drilling jar + 9×jts Φ139.7mm HWDP + Φ139.7mm DP.

This double-stabilizer drill string assembly features stronger stability and pendulum force. During the drilling process, adhering to drilling with the double-stabilizer configuration, and conducting timely wipper trip & reaming operations in long-section large-diameter open hole sections, is conducive to well deviation prevention and correction. This not only ensures wellbore quality but also reduces the time spent on tripping and hole reaming .

3.4 Narrow Mud Weight Window Control Technology

3.4.1 Precision Managed Pressure Drilling (PMPD)

To address the drilling challenges of multi-pressure systems and zero-negative safe mud weight windows in ultra-deep wells of the Zhebachang Structure (northwestern Sichuan) and the Suining-Santai Qixia Formation Slope Structural Belt, precision managed pressure drilling (PMPD) is adopted to tackle the narrow mud weight window. This technology enhances the pressure-bearing capacity of lost circulation intervals through pressure management, expands the safe mud weight window, and ultimately achieves the goals of improving operational efficiency, reducing well control risks, and minimizing complex accidents.

Managed pressure drilling (MPD) technology enables precise control of wellbore pressure, which significantly enhances the controllability of the drilling process, reduces accident probability, and overcomes drilling challenges such as narrow mud weight windows. The technology primarily relies on wellhead equipment and surface manifold systems to finely control or adjust the annular pressure system, ensuring that the annular fluid column pressure is slightly higher than the bottomhole pressure while avoiding formation fracturing. This allows for safe and efficient drilling in intervals with "narrow pressure windows."

Based on the dynamic control model for equivalent circulating density (ECD) [7]:

$$ECD = \rho_m + \frac{\Delta P_{ann}}{0.00981 \cdot TVD}$$

In the formula：

ρ_m—Drilling fluid density（g/cm^3）

ΔP_{ann}—Annular pressure loss（MPa）

TVD—True vertical depth（m）。

Application of Managed Pressure Drilling (MPD) in the Jialingjiang Formation of Well Suitan 1

3.4.2 Dual Mud Weight Drilling Technology

During drilling operations, multi-pressure systems can cause kick-loss transitions (alternating well kicks and lost circulation). The root cause lies in two key issues: first, the safe mud weight windows of individual risk intervals in the well are inherently narrow; second, there are significant differences between the safe mud weight windows of different well intervals. When a single drilling fluid density fails to simultaneously meet the requirements of two or even multiple safe mud weight windows, pressure imbalance occurs in the wellbore.

The principle of Dual Mud Weight Drilling (DMWD) is as follows:

First, through exploration and testing, identify critical pressure parameters for gas-bearing zones, lost circulation zones (risk intervals), and openhole sections—including wellbore stabilization pressure (to prevent kicks), lost circulation pressure (to avoid fluid loss), and the safe mud weight window of each risk interval.Then, for different well intervals, use distinct drilling fluid densities to create tailored hydrostatic pressures.Finally, integrate factors such as wellhead pressure control, annular circulation pressure loss, tripping swab pressure, and tripping surge pressure. This integration ensures that the pressure in each risk interval precisely matches its specific safe mud weight window, achieving dynamic pressure balance across all risk intervals under various drilling conditions.

In practice:During the drilling phase, a lower mud weight limit (2.18 g/cm^3) is used to release formation energy while maintaining wellbore stability.During the tripping-out phase, the mud weight is increased to 2.25 g/cm^3 to ensure well control safety (counteracting swabinduced pressure drops that could trigger kicks).This technology has reduced the kick occurrence rate by 80% [8].

3.5 High-Temperature Drilling Fluid Systems

3.5.1 "Three-Low" Water-Based Drilling Fluid

In the formations above the Xujiahe Formation of the Zhebachang Structure in the northwestern Sichuan Basin, there are highly water-sensitive and highly dispersible shale formations. For these formations, it is necessary to:

Inhibit the hydration and dispersion of drill cuttings to prevent drilling fluid contamination;Prevent the hydration, swelling, and collapse of shale;Avoid wellbore instability caused by water absorption and swelling of the formation wellbore after air drilling (a key downhole challenge).

To address these issues, an organic salt system is first adopted, which offers the following advantages:Facilitates the control of drilling fluid performance;Inhibits the hydration, dispersion, and swelling of rock components, thereby preventing wellbore collapse;Reduces the content of poor-quality drill cuttings in the drilling fluid, as well as the number of micron and submicron particles—both of which help improve the rate of penetration (ROP).On the basis of this organic salt system, technologies related to the "Three-Low" water-based drilling fluid are further incorporated to specifically solve the wellbore instability problem caused by water absorption and swelling after air drilling.

3.5.2 Wettability Reversal Anti-Collapse Technology

After air drilling, the physical properties of the wellbore wall cannot prevent the invasion of drilling fluid and its filtrate in the short term. Additionally, the formation is highly hydrophilic, which easily causes the dry wellbore wall to absorb a large amount of water in a short time—undermining wellbore stability.The core principle of this technology is: If the drilling fluid filtrate can quickly induce wettability reversal of the wellbore wall formation (converting the formation from hydrophilic to oleophilic) and reduce capillary water absorption, the rock strength will not decrease significantly before the filter cake is fully formed. This effectively prevents wellbore collapse.

3.5.3 Low-Permeability Anti-Collapse Technology

The density of kill fluid is usually determined by adding a fixed margin based on the formation pore pressure. This approach easily creates a positive pressure differential between the fluid column and the formation pressure—a differential that has both a positive effect (aiding wellbore stabilization) and a negative effect (risking wellbore instability).The negative impact of this positive pressure differential is as follows: it promotes the invasion of drilling fluid and its filtrate into the formation, which increases pore pressure, triggers interlayer hydration swelling, and reduces rock strength. Importantly, the invasion rate, invasion depth, and water absorption volume of the fluid/filtrate are proportional to the reduction in rock strength—exacerbating wellbore instability.The core solution of Low-Permeability Anti-Collapse Technology is: If the kill fluid can quickly seal micro-fractures in the formation, form a dense hydrophobic internal filter cake and a surface coating, and achieve low fluid permeability, it can inhibit the invasion of drilling fluid/filtrate. This ultimately prevents the reduction in rock strength and wellbore instability.

3.5.4 Low-Activity Anti-Collapse Technology

Since the invasion of filtrate from water-based drilling fluid is an objective and unavoidable phenomenon, the physical and chemical properties of the filtrate become extremely important. Research shows [9]:If the shale activity is lower than that of the drilling fluid, water will infiltrate the shale, triggering surface hydration and osmotic hydration. This process generates high swelling pressure, which damages the wellbore wall—and simply increasing the drilling fluid density cannot counteract this effect.In contrast, if the drilling fluid has lower activity than the shale, water will flow from the formation into the drilling fluid. This causes shale dehydration, which in turn stabilizes the rock strength.

Through optimization, a "Three-Low" formula was developed as follows:4% potassium chloride (KCl) + 0.3% polyacrylamide + 2% sulfonated asphalt + rigid particles (calcium carbonate, $CaCO_3$)/flexible particles (elastic graphite)/fibers (polyester) at a ratio of 3:2:1.Laboratory experiments show that this system reduces the shale swelling rate by 62% (Figure 6) [10].

Through evaluation experiments, the rolling recovery rate (in clear water, 27.5% for the blank group) and linear expansion rate (in clear water, 23.0% for the blank group) of this system were 91.2% and 11.0%, respectively—both higher than those of the KCl-polymer drilling fluid and organic salt-polymer drilling fluid. After adding 5% soil powder, the performance of the drilling fluid showed little change.Regarding the drilling fluid system's filtration performance: its API filtration loss was only 4.2 mL both before and after aging. Additionally, it had strong cuttings carrying capacity, and its comprehensive performance was significantly improved.After the end of blind drilling in Well Zhetan 1, a gas-liquid conversion slurry structure consisting of "Three-Low organic salt poly-sulfonate kill fluid + organic salt poly-sulfonate drilling fluid" was adopted for slurry displacement operation. Drilling was resumed in only 28 hours, and the wellbore remained stable throughout the process.

3.5.5 High-Plugging Oil-Based Drilling Fluid

This drilling fluid adopts the rigid-flexible particle gradation plugging theory (Figure 13) [11-12], with its core plugging mechanism and component functions as follows:

Rigid particles (200-mesh calcium carbonate, $CaCO_3$): Fill large pore throats in the formation to form a primary physical barrier against fluid invasion.Flexible particles (nano-latex): Deform to fit and seal micro-fractures (too small for rigid particles to block), enhancing the integrity of the plugging layer.Fibers (3 mm polyester fibers): Form a network framework that supports rigid and flexible particles, preventing their migration and ensuring long-term plugging stability.

Through optimizing the particle gradation (size distribution of particles) and the proportion of rigid materials, the oil-based drilling fluid's ability to seal micro-pores and micro-fractures in target formations is significantly improved.In the field application of the Ø241.3 mm wellbore in Well Zhetan 1, the fluid achieved a high-temperature high-pressure (HTHP) filtration loss of ≤4 mL—a key indicator of its excellent plugging performance under harsh downhole conditions.

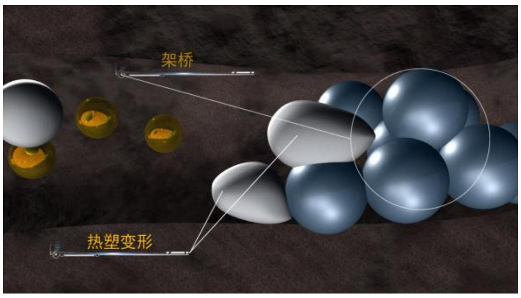


Figure 13 Schematic Diagram of Plugging Based on Rigid-Flexible Particle Gradation

4 Field Application Results

4.1 Significant ROP and Efficiency Improvements

The ultra-deep well safe and efficient drilling technology for northwestern Sichuan was field-applied in Well Zhetan 1 and Well Suitan 1—located in the Zhebachang area and the Suining-Santai Qixia Formation Slope Structural Belt, respectively.Key performance data for the two wells are as follows:

Their average drilling cycle was 427.3 days, and the average rate of penetration (ROP) was 2.70 m/h.Compared with regional offset wells (average drilling cycle: 427.3 days vs. 487 days), the drilling cycle was reduced by 12.26%.Compared with regional offset wells (average ROP: 2.70 m/h vs. 2.35 m/h), the ROP was increased by 17.45%.Notably, the average ROP of the Φ455 mm wellbores reached 4.05 m/h, setting a regional record.

Table 5 ROP Improvement Effect

Indicator	Mean value of offset well	Test Result	Improvement range
ROP	2.35 m/h	2.76 m/h	17.45%
Drilling time	487d	427.3d	12.26%
Fault and complexity rate	14.21%	6.36%	55.24%

4.2 Response to Complex Operating Conditions

4.2.1. Reduction in Failure and Complexity Rates

The average failure and complexity rate of regional offset wells was 14.21%. In contrast:

The failure and complexity rate of Well Zhetan 1 was 4.62%;The failure and complexity rate of Well Suitan 1 was 8.26%;The average failure and complexity rate of the two wells was 6.36%.Compared with the regional average, this represents a reduction of 7.58 percentage points, equivalent to a 55.24% decrease in failure and complexity incidents.

4.2.2. Management of Coexisting Lost Circulation and Kicks

In the Jialingjiang Formation of Well Suitan 1, the combination of Managed Pressure Drilling (MPD) + pressure-bearing lost circulation control (with a lost circulation material concentration of 18%) was adopted. This measure reduced the lost circulation rate from 35 m^3/h to 2 m^3/h, effectively resolving the coexistence of fluid loss and well kicks.

5 Conclusions

Taking "high-efficiency drill bits + high-torque progressive cavity pumps (PCPs)" as the core, and supporting them with deviation prevention and straight-hole drilling technology (mainly dual-stabilizer pendulum assemblies + eccentric stabilizers), can effectively achieve safe and rapid drilling of ultra-deep large-diameter wellbores. Specifically:The combination of bi-center bits and high-torque PCPs increased the ROP of Φ455 mm wellbores by 52.83% and reduced rock-breaking energy consumption by 30%.Meanwhile, the integration of eccentric stabilizers into the dual-stabilizer pendulum drill string assembly enabled precise well deviation control (well deviation ≤ 0.42°).

In response to the risks of ultra-deep wells—including multiple formation pressure gradients, narrow safe mud weight windows, and coexisting lost circulation and kicks—the application of Managed Pressure Drilling (MPD) and the dual mud weight process reduced the complexity rate of narrow mud weight window intervals (≤0.05 g/cm³) by 69.28%.

By incorporating "Three-Low" drilling fluid-related technologies (wettability reversal anti-collapse technology, low-permeability anti-collapse technology, and low-activity anti-collapse technology), and optimizing the development of a high-plugging oil-based drilling fluid based on the rigid-flexible particle gradation plugging theory, a supporting technology system was formed. This system addresses wellbore collapse in large-diameter wellbores and provides high-temperature resistance for deep oil-based drilling fluids, ultimately improving plugging efficiency by 40%.

The successful application of this technical system in the Zhebachang area and the Suining-Santai Qixia Formation Slope Structural Belt of the Sichuan Basin provides a reliable solution for drilling ultra-deep wells deeper than 9000 m in northwestern Sichuan.

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