RESEARCH ARTICLE

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Displacement and Pressure Control for Reaming of Blocked Horizontal Shale Gas Wells

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Abstract

Shale gas horizontal wells in the Hongxing Block are challenged by long horizontal sections, narrow annular clearances, well-developed fractures, and the coexistence of lost circulation and wellbore collapse. Complexities such as pipe sticking, pump surging, annular blockage, and cuttings accumulation frequently occur during reaming, severely affecting operational safety and efficiency. To overcome the drawbacks of conventional empirical methods, this paper establishes four quantitative models: displacement-pressure coupling, bottomhole Equivalent Circulating Density (ECD) constraint, critical cuttings transport displacement, and drill string safety loading. An integrated reaming technology involving staged displacement, closed-loop emergency treatment, bi-directional reaming, and segmented circulation is then developed. Field application in Well Hong 3-5HF and multi-well verification demonstrate that the proposed method reduces the reaming complication rate from 15% to below 6.2% and achieves a 100% one-trip success rate in the three application wells tested in this study. This work provides a standardized technical solution for safe and efficient reaming in the Hongxing Block and similar shale gas fields.

Keywords: hongxing block, reaming, segmented circulation, annular pressure buildup, horizontal well.

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1 Introduction

Long horizontal sections of shale gas wells commonly suffer from severe cuttings accumulation, hydration-induced wellbore spalling, and extremely narrow formation pressure windows. The control of circulating displacement and equivalent circulating density (ECD) during reaming and tripping operations is critical to wellbore safety. Insufficient displacement significantly weakens cuttings transportation efficiency, resulting in thick cuttings beds that easily induce pipe sticking and pump pressure buildup. In contrast, excessive displacement may exceed the formation pressure bearing capacity, aggravate wellbore erosion and collapse, and

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Figure 1. Tectonic location and well distribution map of the Hongxing Block.
*Note: This figure shows the overall tectonic division of the study area and the spatial distribution of existing horizontal wells, which reflects the layout characteristics of shale gas development wells in the block.

trigger lost circulation, thereby increasing downhole treatment costs. Therefore, developing a precise regulation method for safe displacement and annulus pressure in resistant intervals, which comprehensively balances hole cleaning, wellbore stability and pressure constraints, is of important research significance [1–3].

Plenty of studies have focused on horizontal wellbore cleaning, ECD control and reaming safety. Mahmoud et al. [4] analyzed the formation rules of cuttings beds and established critical cuttings transport criteria. Al-Rubaii et al. [5] pointed out that narrow annuli are high-risk areas for downhole complexities. Abbas et al. [6] verified the influences of pipe rotation and cuttings size on hole cleaning performance. Tan and Zhang [7] proposed a risk prediction method for stuck-pipe accidents caused by wellbore uncleanness in long horizontal section wells, quantifying the relationship between cuttings bed thickness and pipe sticking probability. Chen et al. [8] developed a transient cuttings transport model for backreaming operations in long horizontal wells, revealing the competing "cleaning" and "plugging" effects of large-size drilling tools on cuttings bed dynamics and stuck-pipe risk during back reaming. In terms of pressure management, Kazemi et al. [9] developed an integrated simulation model to optimize hole cleaning efficiency in horizontal shale wells, demonstrating that displacement scheduling and circulation staging significantly improve cuttings transport ratios. Dokhani et al. [10] explored the wellbore instability mechanism of shale formations. Erge et al. [11], Tang et al. [12] and Oguta and Ihua-Maduenyi [13] successively established various ECD prediction models for horizontal and extended-reach wells.

This study establishes an integrated reaming control technical system based on four quantitative safety boundary calculation models, targeting the challenging reaming conditions encountered in long horizontal shale gas wells of the Wujiaping Formation in the Hongxing Block. Based on annular hydraulic principles and shale wellbore stability mechanics, four sets of computational equations regarding displacement–pump pressure coupling, bottom-hole ECD constraints, critical cuttings transport displacement, and drilling tool safe load are derived. Wellbore stability analysis incorporating formation hydration effects provides the collapse-pressure boundary essential for defining the safe mud-weight window [14]. The corresponding safety thresholds of circulation displacement, pump pressure, equivalent circulating density, and tripping load are quantitatively determined to realize pre-judgment of downhole parameters [15]. This work fills the technical gap regarding integrated solutions for graded parameter regulation and closed-loop pump-pressure-overload emergency disposal during reaming operations in slim narrow-annulus wells.

2 Background and Methodology

2.1 Engineering Background

As a key exploration and development target in eastern Sichuan, the marine shale gas reservoirs of the Wujiaping Formation in the Hongxing Block are vertically overlain by Jurassic, Triassic, and Permian strata. The thickness of the shallow Jurassic strata varies significantly across the block due to differential denudation (Figure 1). The study area is characterized by alternating continental sand-mudstone and marine limestone-shale sequences with normal compaction and no abnormal high formation pressure. Reaming operations during well drilling and completion commonly encounter severe downhole problems, including frequent tight spots, recurring pump pressure buildup, poor annulus flow capacity, and coexisting lost circulation and wellbore collapse [16–18, 20].

The major drilling difficulties are as follows: (i) high lost-circulation and collapse risks in long open holes of the second spud, with low success in plugging and pressure enhancement; (ii) high horizontal stress difference and well-developed microfractures in the Wujiaping Formation, leading to lost circulation and wellbore instability.

Statistics from 2024 show that lost circulation accounts for 66.06% of all downhole complexities in the study area, with major loss zones in the Shaximiao, Xujiahe, and Jialingjiang Formations. Wells such as Hong 9HF, Hong 18-4HF, and Hong 18-5HF experienced total losses, with a total mud loss of 7292.34 m^3. Wellbore instability concentrates in the Ziliujing Formation in the central area, where severe sloughing occurs (maximum cavings: 10 cm×9 cm×5 cm), with the longest treatment duration reaching 11.77 days. The target Wujiaping and Changxing Formations also present high risks: all four pilot wells encountered issues, including three cases of annular restriction and two cases of lost circulation, totaling 32.32 days of NPT. Plugging efficiency is low and recurrence is high under oil-based mud.

Spatially, complexities follow a pattern: prone to loss at northern and southern margins, prone to collapse in the central area, and coexistence of loss and collapse. Marginal wells feature well-developed fractures and low pressure-bearing capacity, leading to losses even at low densities. Central wells require high densities to stabilize the Ziliujing mudstones, which may trigger upper losses. Small annular clearances, casing centralizer-induced cavings, and poor cuttings transport collectively cause frequent sticking, pump surging, and annular restriction during reaming [19, 20]. Conventional experience-based operations can no longer ensure safety, demanding a quantitative and standardized reaming method with safe displacement and pressure control.

2.2 Calculation Methods

Field operations include three core steps: collection of key parameters, calculation of four safety boundaries, selection of reaming BHA, and tripping and reaming.

2.2.1 *Four Safety Boundary Calculation Models*

Displacement-pressure coupling model: Establishes a quantitative relationship between total pump pressure and pressure losses in drillstring, annulus, and bit, determines flow regime index n, and enables theoretical pump pressure prediction at variable flow rates [21]. The formula is:

$$P_{\text{total}} = P_{\text{drillstring}} + P_{\text{annulus}} + P_{\text{bit}} \tag{1}$$

$$\frac{P_1}{P_2} = \left(\frac{Q_1}{Q_2}\right)^n \tag{2}$$

where P_{total} is the total pump pressure (MPa); $P_{\text{drillstring}}$, P_{annulus}, and P_{bit} are the inner pressure loss of the drillstring, the annular pressure loss, and the bit pressure drop (all in MPa), respectively; Q_1 and Q_2 are different flow rates (m^3/h); P_1 and P_2 are the corresponding pump pressures at Q_1 and Q_2 (MPa); and n is the flow regime index, ranging from 1 for laminar flow to 2 for fully turbulent flow, determined by curve fitting from field measurements.

Bottomhole ECD dynamic constraint model: Takes formation lost-circulation equivalent density as the upper limit to calculate maximum allowable annular pressure loss and total pump pressure, preventing ECD-induced lost circulation [22]. The formula is:

$$\rho_{\text{ECD}} = \rho_{\text{mud}} + \frac{P_{\text{annulus}}}{g \times H \times 10^{-3}} \tag{3}$$

$$P_{\text{annulus, max}} = (\rho_{\text{loss}} - \rho_{\text{mud}}) \times g \times H \times 10^{-6} \tag{4}$$

$$P_{\text{total, max}} = P_{\text{annulus, max}} + P_{\text{drillstring}} + P_{\text{bit}} \tag{5}$$

where ρ_{ECD} is the bottomhole equivalent circulating density (g/cm^3); ρ_{mud} and ρ_{loss} are the drilling fluid density and the equivalent density of formation lost circulation (both in g/cm^3), respectively; g is the gravitational acceleration (9.8 m/s^2); H is the current well depth (m); and $P_{\text{annulus, max}}$ is the maximum allowable annular pressure loss (MPa).

Critical cuttings transport displacement model: Calculates minimum flow rate Q_{min} using annular cross-sectional area and critical transport velocity to avoid cuttings bed buildup [23]. The formula is:

$$A_{\text{ann}} = \frac{\pi}{4} \times \left(D_{\text{hole}}^2 - D_{\text{dp}}^2\right) \tag{6}$$

$$Q_{\text{min}} = \frac{v_{\text{cr}} \times A_{\text{ann}} \times 3600}{4} \tag{7}$$

where A_{ann} is the annular cross-sectional area (m^2); D_{hole} and D_{dp} are the hole diameter and the outer diameter of the drill pipe (both in m), respectively; v_{cr} is the critical cuttings transport velocity (m/s), which ranges from 0.8 to 1.2 m/s depending on cuttings size; and Q_{min} is the minimum cuttings transport flow rate (m^3/h), used as the lower displacement control limit after conversion to strokes per minute (spm). The denominator 4 in Eq. (7) performs this conversion based on the rated pump displacement of 1 L/stroke for the triplex pump deployed in the Hongxing Block; this factor should be adjusted according to the actual pump specifications at other field sites.

Drill string safety loading model: Determines maximum allowable pull force F_{max} based on yield strength, safety factor, and friction coefficient to prevent stuck pipe during tripping. The friction model accounts for the interaction between the drillstring and cuttings bed, as cuttings accumulation at the low side of horizontal sections significantly increases the effective drag force on the drill string [24]. The formula is:

$$F_{\text{max}} = F_{\text{yield}} \times S - F_{\text{friction}} \tag{8}$$

$$F_{\text{friction}} = f \times W_{\text{dp}} \tag{9}$$

where F_{max} is the maximum allowable pull load (t); F_{yield}, F_{friction}, and W_{dp} are the yield strength of the drilling tools, the tripping friction load, and the weight of the drillstring in drilling fluid (all in t), respectively; S is the safety factor, taken as 0.7–0.8 in field practice; and f is the friction coefficient, ranging from 0.1 to 0.3 depending on wellbore conditions.

2.2.2 *Staged Displacement Startup and Stepwise Increase*

A unified protocol is applied: low flow rate (7–18 m^3/h) to establish circulation, followed by stepwise increases. Flow rate is raised by 5 spm (approximately 0.3 m^3/h per increment) every 10 min in the low-rate stage, and by 2 spm every 5 min in the high-rate stage. Pump pressure is predicted before each increase to ensure compliance with safety limits and stable fluid level. The recommended displacement range by hole size is 24.0–28.0 m^3/h for a ϕ190.5 mm hole and 30.0–35.0 m^3/h for a ϕ215.9 mm hole.

2.2.3 *Emergency Response for Pump Surging*

In case of excessive pump pressure or top-drive shutdown, immediately reduce to 20 spm, reciprocate drill pipe within 20–30 m and F_{max}. After stabilization, resume flow rate in 5-spm steps and verify normal circulation before further increase.

2.2.4 *Bi-directional Reaming and Segmented Circulation*

The top drive is started in stages to 20 rpm and 50 rpm. Back reaming at 30 rpm and forward reaming at 50 rpm are conducted for at least 2 full cycles. Segmented circulation is performed at 60° inclination, A-target point, and every 600–800 m along the horizontal section. Pumping is initiated actively 3 stands above the bottom to ream to total depth, and high-speed circulation is used to clean settled cuttings in the wellbore.

2.2.5 *Tripping Control and Drilling Fluid Management*

Tripping in: speed $\leq$ 0.8 m/s in cased hole, $\leq$ 0.5 m/s in open hole, and $\leq$ 0.3 m/s in special intervals. Tripping out: fill up on every stand; load shall not exceed F_{max}. Drilling fluid is maintained as flat laminar flow with solid content $\leq$ 25%, enhanced inhibition and plugging capacity. Density, return flow rate and fluid level are monitored in real time. Pumping should be stopped immediately upon detection of any anomaly.

3 Results and Discussion

3.1 Single-Well Application

The field verification well selected in this study is Well Hong 3-5HF, with a designed total depth of 6820 m. The third spud adopts ϕ190.5 mm wellbore and ϕ139.7

Table 1. Operation parameters and duration of each displacement stage in Well Hong 3-5HF.

Operation Stage	Displacement	Duration	Average Pump Pressure (MPa)	Reaming Passes	Peak Torque (kN·m)	Average ROP (m/h)
Emergency circulation	20 spm (5 L/s)	30 min	12.3	1	18.6	2.1
Recovery to critical displacement	11 m^3/h	60 min	6.2	1	16.2	2.5
Intermediate adjustment stage	15 m^3/h	45 min	8.7	1	17.1	2.3
Normal reaming stage	20 m^3/h	120 min	15.5	2	19.3	2.8

Table 2. Operation performance of wells adopting the proposed standardized technology.

Well ID	Well Type	Complication Type	Planned NPT/h	Actual NPT/h	Saved NPT/h	One-trip Success Rate	Complication Rate/(%)	ECD Compliance Rate
Hong a	Slim-II	Pump surge, annular restriction	304.9	84.6	220.3	100%	6.2	100%
Hong b	Slim-II	Annular restriction, cavings	48.2	22.1	26.1	100%	4.1	100%
Hong c	Conventional	Collapse, cuttings bed	120.7	46.8	73.9	100%	3.5	100%

mm casing, and the horizontal section is deployed in the Wujiaping Formation. The on-site drilling fluid density is 1.40 g/cm^3, plastic viscosity is 26 mPa·s, and solid content is 22%. The equivalent density of formation lost circulation is 1.65 g/cm^3. A pump stalling accident occurred at the well depth of 6764.06 m during reaming.

Root cause analysis of pump stalling: Long-term cuttings accumulation formed thick cuttings beds at the low side of the horizontal section. Under narrow annular clearance conditions, cuttings were compacted to block the annulus, which led to rapid pump pressure rise and final pump stalling. No equipment failure or formation collapse was detected after inspection.

Displacement-pressure coupling model: Field measurements show that pump pressure is 9.7 MPa at 20 m^3/h and 2.7 MPa at 11 m^3/h. The fitted flow regime index is $n = 2.14$ (turbulent flow).

Bottomhole ECD dynamic constraint model: The calculated maximum allowable annular pressure loss is

$$P_{\text{annulus, max}} = (1.65 - 1.40) \times 9.8 \times 6764.06 \times 10^{-3} \approx 16.57 \text{ MPa}.$$

Combined with drillstring pressure loss of 5.2 MPa and bit pressure drop of 0.8 MPa, the maximum total pump pressure is

$$P_{\text{total, max}} = 16.57 + 5.2 + 0.8 = 22.57 \text{ MPa}.$$

Critical cuttings transport model: For a ϕ190.5 mm hole and ϕ139.7 mm casing, the annular cross-sectional area is $A_{\text{ann}} = \frac{\pi}{4}(0.1905^2 - 0.1397^2) \approx 0.0132 \text{ m}^2$. With $v_{\text{cr}} = 1.0$ m/s, the minimum transport rate is calculated as $Q_{\text{min}} = \frac{1.0 \times 0.0132 \times 3600}{4} \approx 11.9 \text{ m}^3/\text{h}$ (equivalent to 3.3 L/s), which is consistent with the field recovery displacement of 11 m^3/h adopted in the first stabilization stage after the pump stalling accident.

Drill string safety loading model: For ϕ139.7 mm casing with a yield strength of 220 t, a safety factor of 0.7, a friction coefficient of 0.15, and a drillstring weight of 90 t, the calculated maximum allowable pull load is

$$F_{\text{max}} = 220 \times 0.7 - 0.15 \times 90 = 140.5 \text{ t}.$$

The detailed operation parameters and duration of each displacement stage in Well Hong 3-5HF are summarized in Table 1.

After the pump stalling accident, as documented in Table 1, the displacement was immediately reduced from the normal reaming rate of 20 m^3/h to 20 spm (5 L/s) for emergency circulation. The drill string was reciprocated within a 28 m interval. Although the theoretical maximum allowable pull load was calculated as 140.5 t, the actual pull load during some reciprocating strokes reached 170 t due to severe tight-hole conditions. This indicates that the operational limit was exceeded in practice, highlighting the need for more conservative tripping parameters or enhanced hole conditioning before reaming in similar scenarios.

Then the displacement was restored step by step to 11 m^3/h (critical transport displacement) and kept stable for 1 hour. After confirming normal circulation, the displacement was increased to 15 m^3/h, with a stable pump pressure of 6.2 MPa, which is far below the maximum safe pump pressure of 22.57 MPa. A large number of rock blocks and cuttings were discharged from the shale shaker after 1 hour of circulation, realizing effective cuttings removal.

Finally, the displacement was increased to 20 m^3/h (within the safe range for ϕ190.5 mm wellbore). The pump pressure fluctuated between 15 MPa and 16 MPa. Segmented circulation was implemented for 2 cycles

Cavings from Well Hong d (7×5×3 cm) Cavings from Well Hong e (7×5×2 cm)

Figure 2. Typical cavings.

Table 3. Operation performance of wells adopting traditional empirical methods.

Well ID	Non-compliance	Complication Type	Treatment Time/h	Recurrence	Final Success Rate	Failure Cause
Hong d	Skipped $Q_{\min}$, direct high-rate startup	Loss, collapse, pump surge	192.5	4	60%	Excessive ECD, aggravated loss
Hong e	No rate reduction during surge, forced pumping	Coexisting loss and collapse	148.3	3	70%	Compacted cavities, annular throat
Hong f	No segmented circulation, insufficient transport	Cuttings bed, stuck pipe	96.7	2	75%	Low-side buildup, lost circulation

at the well depth of 6741.00 m to thoroughly remove cuttings. The reaming operation was completed after all parameters remained stable. Subsequent casing running and hanger setting were finished smoothly. The circulating pressure remained normal during cementing operation, cement slurry returned to the surface successfully, and the annular pressure test reached 28 MPa without any anomalies.

3.2 Multi-Well Comparative Application

To further verify the field applicability of the proposed safe displacement and pressure control technology for annular blockage reaming, this study selects 6 wells in the Hongxing Block for comparative analysis, including 3 wells adopting the proposed standardized technology (treatment group) and 3 wells serving as a control group that adopted traditional empirical methods without applying the new technology. Key evaluation indicators include treatment efficiency, complication rate, one-trip success rate and ECD compliance rate (Tables 2 and 3, Figure 2).

(1) **Baseline data source:** The historical reaming complication rate of the Hongxing Block is 15%, which is statistically calculated from 42 horizontal wells drilled in 2022–2024 (data from Jianghan Petroleum Engineering Drilling Database).

(2) **Well selection criteria:** The 6 test wells have similar well depth, horizontal section length, wellbore size and formation lithology, which ensures the comparability of working conditions. All wells are constructed after the formation of this technology, and the control group actively abandons the new technology and adopts traditional empirical methods for comparison.

(3) **Sample explanation:** 6 wells are included in the verification, and the one-trip success rate of the 3 application wells reaches 100%.

Data analysis:

(1) The average NPT reduction rate of the three wells reaches 62.5%, among which Well Hong a saves 220.3 h of non-productive time. The staged displacement, segmented circulation, and closed-loop emergency disposal technology have

fundamentally resolved the problems of rock block accumulation, pump pressure surge, and annular restriction.

(2) The reaming one-trip success rate of the application group is 100%, and the complication rate is reduced from the historical baseline of 15% to below 6.2%. The four safety boundary models have jointly enabled the integrated control of lost circulation prevention, wellbore collapse prevention, and pipe sticking prevention.

(3) The ECD compliance rate of all three wells is 100%, and the pump pressure fluctuation is controlled within ±0.5 MPa. Stepwise displacement increase effectively avoids instantaneous pressure surge, and prevents lost circulation in upper fractured formations. Moreover, gradual flow rate escalation ensures continuous cuttings mobilization from the low side of the horizontal section, avoiding the sudden release of large cuttings slugs that would otherwise cause abrupt pressure spikes [25].

Analysis of control group wells:

(1) Well Hong d did not calculate the safety boundary of critical displacement and ECD. Direct high-rate pumping caused excessive annular pressure loss and ECD exceeding the formation pressure-bearing limit, which induced total lost circulation.

(2) Well Hong e failed to reduce displacement in time after pump surging and adopted forced reaming. Rock blocks were compacted in the narrow annulus to form blocking throat, resulting in long-term failure to re-establish normal circulation.

(3) Well Hong f did not implement segmented circulation. A large number of cuttings accumulated at the low side of the horizontal section and finally induced cuttings-bed sticking.

All failed wells abandoned quantitative model calculation and standardized procedures. The uncontrolled displacement and pressure, combined with inadequate wellbore cleaning, led to repeated complexities, which fully proves the necessity of the proposed technology.

Combined with the data of 6 test wells, the overall statistical indicators are summarized as follows. The average NPT reduction rate of the technology application group is 62.5%, with a standard deviation of 7.4%. The overall reaming complication rate drops from 15% (historical average) to 4.6% (average of 3 application wells). The one-trip success rate of reaming reaches 100% for wells adopting the standardized process. The ECD compliance rate of all application wells is 100%, and the pump pressure fluctuation range is controlled within ±0.5 MPa.

3.3 Integrated Discussion

A comparison of domestic and international reaming technologies is presented in Table 4, which reveals obvious technical gaps between domestic and international well circulation technologies. Foreign services including Schlumberger and Halliburton own mature hydraulic simulation tools, yet their algorithms are developed for standard boreholes, lacking adaptability to domestic slim-hole shale wells with extremely narrow pressure windows. Current industrial practices adopted by CNPC and Sinopec mostly rely on field experience, with discharge control accuracy merely ±10%–15%. Statistical data from the Hongxing Block reveal an 18% complex accident rate during wiper trips, due to the absence of quantitative safety boundary calculation. The integrated technique proposed in this paper quantifies four critical safety limits and matches staged circulation plus closed-loop pumping stall disposal. It narrows pressure control error down to ±3%–5%, effectively solving coupled wellbore risks of collapse and lost circulation, and provides targeted standardized procedures for Sinopec's Hongxing shale gas block.

Novelties of this study: Based on the four established models, full-process safety operation windows are quantitatively determined. Accordingly, standardized operational procedures are developed, including graded stepwise displacement increasing, bidirectional alternating reaming, segmented circulating cutting cleaning, and rapid pressure buildup disposal. Combined with auxiliary control measures such as drilling fluid inhibition and plugging performance management and tripping speed restriction, a complete technical framework integrating model-based quantitative prediction and standardized process disposal is formed. The feasibility and effectiveness of the proposed technical system have been fully verified through field applications and comparative analysis based on the Hong 3-5HF well and multiple actual drilling wells in the block.

Although this study is more closely aligned with field operations, and the functionally formulated empirical

Table 4. Comparison of Existing Methods and Proposed Method.

Technology Source	Representative Technique	Core Features	Displacement Control Accuracy	Applicable Scenarios
Schlumberger (Foreign)	Hydraulics Simulation	Steady-state hydraulic single model	±8%-12%	Conventional large displacement wells
Halliburton (Foreign)	Wellbore Routine	Empirical fixed discharge scheme	Qualitative, no threshold	Ordinary wells, poor for narrow window
CNPC Chuanqing Drilling	Segmented Circulation Process	Empirical rotation displacement adjustment	±10%-15%	Marine shale, not fit slim-hole wells
Sinopec Jianghan Engineering	Conventional Reaming Specification	Empirical operation without quantitative limit	Qualitative, block complex rate ~ 18%	Fuling Hongxing conventional wells
This Study	Four Safety Boundaries Integrated System	Quantified threshold + staged regulation + emergency closed-loop	±3%-5%	Slim-hole wells with simultaneous lost circulation collapse

operating procedures provide better targeting and higher success rates for on-site reaming compared with previous studies, limitations still exist in coupling analysis, such as:

(1) **Simplified model boundary conditions.** The calculations assume stable drilling fluid properties, formation leakage pressure, and wellbore geometry. They do not fully account for the real-time effects of caving transport, wellbore spalling, and dynamic activation of loss zones on ECD and annular pressure loss during reaming.

(2) **Insufficient working condition adaptability validation.** Field applications were mainly concentrated in slim-hole Type II wells and the Wujiaping Formation shale in the Hongxing Block. The versatility and stability for ultra-long horizontal sections, tighter clearances, ultra-high friction wells, and severe loss wells lack multi-region and large-sample verification.

(3) **Insufficient dynamic mechanism research.** This study focuses on macro engineering parameters and field performance. It does not deeply investigate microscopic and dynamic mechanisms such as caving bridging kinetics, transient annular flow field behavior, and real-time ECD fluctuation laws. The models remain semi-empirical and semi-theoretical.

Scientific safety window calculation and data calibration are the prerequisites for handling complex downhole faults, while functional operating specifications enable full utilization of field experience and provide feasible operational parameters for each construction step. Targeting poor reaming performance caused by annular blockage and pressure buildup, the corresponding engineering guidelines are proposed as follows:

Pre-control Measures (Pre-operation)

(1) **Engineering pre-control.** Before entering intervals prone to lost circulation, collapse and blocking, it is mandatory to complete calculations of four models including displacement-pressure coupling, ECD, critical cuttings transport and drillstring load, and clarify the safety boundaries of $Q_{\min}$, $Q_{\max}$, P_{total}, $P_{\max}$. Strictly control tripping-in speed: ≤ 0.8 m/s inside casing, ≤ 0.5 m/s in open hole intervals, and ≤ 0.3 m/s in special intervals. Implement the segmented circulation system at a deviation angle of 60°, target point A, and every 600–800 m in horizontal sections to actively clean the wellbore.

(2) **Drilling fluid pre-control.** Maintain the drilling fluid with strong inhibition, effective plugging and low solid content, with the solid content controlled within 25%. Optimize the yield-point plastic-viscosity ratio to maintain flat laminar flow in the annulus. Supplement plugging agents and inhibitors before entering the Ziliujing Formation and Wujiaping Formation, and strictly control API fluid loss within 3 mL to prevent wellbore spalling and cavings.

(3) **Geological risk pre-control.** Sort out the lost circulation, collapse and caving intervals of adjacent wells in advance, issue early warnings for fracture-developed intervals, ant-body anomalies and sections with abrupt structural dip angles, reduce displacement and conduct stable operations to avoid downhole complications induced by surge pressure.

Disposal Measures (On-site Operation)

(1) **Emergency disposal for pump surging.** Once pump surging or top drive stall occurs, immediately reduce the flow rate to the emergency displacement of 20 strokes per minute,

and forced pressurization is strictly prohibited. Reciprocate the drilling string within 20–30 m with the load not exceeding F_{max}. After the pump pressure stabilizes, restore the displacement gradually in small increments of 5 strokes per minute, and further increase the displacement only after no abnormality is confirmed by circulation.

(2) **Reaming disposal for tight hole resistance.** For tight hole resistance, forced tripping up and down are forbidden. Adopt the combined mode of low-revolution back reaming and high-revolution forward reaming, and remove cavings and cuttings beds through segmented circulation. Reaming can be continued only when cuttings return cleanly from the shale shaker and pump pressure remains stable.

(3) **Disposal for coexisting lost circulation and wellbore collapse.** Once lost circulation occurs, immediately reduce the displacement to the safe range above Q_{min}. Prioritize the application of fine particle bridging slurry while conducting drilling lost circulation control, and indiscriminate increases in fluid density and displacement are strictly prohibited. In case of severe wellbore collapse and massive cavings, carry cuttings with high-viscosity and high-shear thick slurry first, then inject cement slurry to stabilize the wellbore, so as to prevent the deterioration of downhole complications.

4 Conclusions

This study targets high-frequency reaming-related issues (sticking, pump surging, annular restriction, coexisting loss and collapse) in horizontal shale gas wells in the Hongxing Block. Four safety-boundary models and an integrated technical system are established and validated, providing a replicable method for safe displacement-pressure control and reaming.

(1) Standardized workflows reduce complication rates from 15% to below 6.2%, achieve 100% one-trip success, reduce non-productive time by over 60% on average, and demonstrate excellent performance in pressure control, loss prevention, stuck-pipe avoidance, and hole cleaning.

(2) Low-solid, inhibitive, plugging, flat-laminar mud, combined with segmented circulation and bi-directional reaming, stabilizes wellbores and removes cuttings beds, matching the sloughing-prone Ziliujing and Wujiaping Formations.

(3) Future work will improve dynamic coupling of annular flow and caving transport, expand validation to ultra-long laterals, ultra-slim holes, and severe-loss wells, and refine micro-mechanisms and model accuracy.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

Kui Li and Ye Yang are affiliated with the Drilling Company No.1 of Sinopec Jianghan Petroleum Engineering Co., Ltd. Qianjiang 433123, China; Li Gong is affiliated with the Sinochem Holdings Corporation Ltd. Baoding 070001, China; Chao Yang is affiliated with the Sinopec Jianghan Oilfield Company Fuling Shale Gas Company, Fuling 408102, China; Xiaokui Hu is affiliated with the Shale Gas Mining Technology Service Company, Sinopec Jianghan Petroleum Engineering Co., Ltd., Wuhan 430075, China. The authors declare that these affiliations had no influence on the study design, data collection, analysis, interpretation, or the decision to publish, and that no other competing interests exist.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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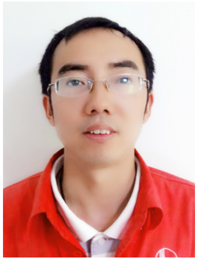

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