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Drilling Technology Route and Safe Drilling Technology for Dengying Formation Gas Reservoirs in the Sichuan Basin

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Abstract: Objectives The Dengying Formation gas reservoirs in the Sichuan Basin are characterized by great burial depth, multiple superimposed pressure systems and strong reservoir heterogeneity. During drilling, risks such as the coexistence of kick and lost circulation, borehole collapse and pipe sticking, high temperature and high pressure (HTHP), and sour-gas well control are superimposed, which severely restricts optimized-fast drilling and beneficial production. Methods Taking the Gaoshiti–Moxi block, the Penglai gas field and the Daxingchang block as key objects, five geological and engineering constraints were quantitatively characterized. A casing program design methodology with "accurate formation pressure prediction—efficient safety-window expansion—casing program optimization and extension" as the main line was established. Ten key technologies were developed, covering accurate wellbore pressure control, kick/loss early warning and treatment, ultra-high temperature drilling fluid, efficient rock breaking and ROP improvement, measurement/logging while drilling, ultra-deep liner cementing, high-strength coring, digitalization and well control. A drilling program was further designed and verified for the new Pengshan–Qingshen block. Results A formation pressure prediction model combining the improved variable-exponent Eaton method for sand–mudstone and the Bowers effective-stress method for carbonate rocks was established, increasing formation pressure-bearing capacity by 0.22 g/cm³. A "five-to-six spud conventional plus non-standard" casing program series was developed; the ultra-large-size managed pressure drilling (MPD) equipment achieves a wellhead pressure control accuracy of ± 0.07 MPa under a 680 mm main bore and a flow rate of 150 L/s. In the Dengying Formation of the Gaoshiti–Moxi block, the "micro-overbalance with micro-loss" MPD mode reduces mud loss by 81% and complex time by 92.4%. The 260 °C oil-based drilling fluid system reaches a maximum density of 2.60 g/cm³,

and the JFS PLUS water-based system shortens the horizontal-section drilling cycle by 35.03% compared with oil-based fluid. The self-developed rotary steerable system has accumulated 6 806 m of footage and increased the rate of penetration (ROP) by over 60%. Automatic managed-pressure cementing and the high-strength, high-toughness anti-channeling cement slurry increase the cementing qualification rate by 25%, with over 500 field applications. Conclusions The technology system has been applied in more than 300 wells across three blocks, reducing drilling fluid loss by over 84% and complex loss time by over 81% year on year. It has supported the Asian deepest vertical well record of 9 026 m in Well Pengshen 6 and the 299 d drilling cycle record in Well Dashen 102, providing a reference for safe and optimized-fast drilling of similar deep carbonate gas reservoirs in China and abroad.

Keywords: Dengying Formation gas reservoir; deep and ultra-deep well; casing program optimization; managed pressure drilling; ultra-high temperature drilling fluid; ROP improvement tool; MWD/LWD; ultra-deep liner cementing; well control safety

1. Introduction

Deep and ultra-deep strata have become the primary domain for increasing natural gas reserves and production in China, and the drive toward greater depths has substantially increased the dependence on engineering technology[1]. The Upper Sinian Dengying Formation is one of the most strategic replacement plays in the Sichuan Basin. Following the discovery of the Weiyuan gas field, the recognition of the Deyang–Anyue rift and the establishment of the composite accumulation model involving "paleo-high, paleo-rift, paleo-erosion surface and paleo-trap" led to successive breakthroughs in the Anyue gas field, the Penglai gas area and the Daxingchang block, indicating a resource scale of the order of one trillion cubic meters[2][3]. There is, however, a marked contrast between resource endowment and engineering feasibility. The Dengying Formation is mainly buried at 5 000–6 500 m, the overlying strata exhibit repeatedly alternating pressure systems, the reservoir space is dominated by fractures and vugs and is highly pressure-sensitive, and hydrogen sulfide is commonly present together with elevated formation temperature. Drilling has long been trapped in a passive situation characterized by difficulty in "drilling to target, drilling fast, and drilling well"[4][5].

On the supply side of technology, recent research has advanced broadly along three paths. Along the wellbore pressure control path, Zhou Yingcao et al. traced the evolution of MPD equipment from semi-automation to automation and intelligentization, and argued that the essence of the technology lies in transforming bottomhole pressure from "static density balancing" into "dynamic pressure profile regulation", thereby making it possible to accommodate multiple pressure systems within a single openhole interval[6]. Liu Wei et al.

further noted that the integration of MPD with artificial intelligence ultimately rests on early identification of downhole complex conditions and on a closed decision-making loop[7]. Li Zhilin et al. developed large-bore MPD equipment for the special conditions of large upper hole sizes and high flow rates, where natural throttling is pronounced[8]. Along the wellbore working fluid path, Sun Jinsheng et al., starting from the microscopic mechanisms of additive degradation, cross-linking and conformational transition under high-temperature and high-salinity conditions, proposed that water-based systems should prioritize high-temperature stability while oil-based systems should focus on environmentally friendly high-temperature stabilizers and rheology modifiers[9]. Along the rock breaking and measurement path, progress in customized PDC bits, torsional impact hammers and high-temperature MWD tools has jointly expanded the scope for ROP improvement in difficult formations.

The difficulty is that these achievements mostly address a single link or a single set of boundary conditions, whereas the challenge of the Dengying Formation lies precisely in the simultaneous action of multiple factors: multiple pressure systems superimposed vertically, a safety density window approaching zero, a high-temperature and sour reservoir, and strongly abrasive rock. These four factors are not simply additive; they amplify one another through multi-field coupling of pressure, temperature, chemistry and mechanics, so that improvement in any single technology is unlikely to be effective on its own. Wu Xianzhu et al. previously provided a systematic review of drilling and completion technologies for deep carbonate rocks in the Sichuan Basin[4], but their understanding was formed mainly at the end of the 13th Five-Year Plan period. It does not incorporate the drilling data accumulated in recent years in new areas such as the Penglai gas area and the Daxingchang block, nor does it cover recent breakthroughs such as 260 °C grade oil-based drilling fluids and ultra-large-size, high-flow-rate MPD equipment, and it offers no replicable program template for frontier areas with low exploration maturity.

In view of this, this paper is based on the drilling practice of CNPC Chuanqing Drilling Engineering Co., Ltd. in three blocks—Gaoshiti–Moxi, the Shehong–Yanting area of the Penglai gas field, and Daxingchang. It first quantitatively characterizes the geological and engineering constraints of the Dengying Formation, then constructs a technology system covering ten links (casing program, pressure control, kick/loss treatment, drilling fluid, ROP improvement tools, MWD/LWD, cementing, coring, digitalization and well control), and finally completes a program design and risk assessment for the Pengshan–Qingshen block, which has a low degree of exploration. The aim is to establish a complete technology route running from problem identification through technology configuration to verification in a new area.

2. Regional Geological Characteristics and Engineering Challenges

2.1 Vertically Superimposed Pressure Systems and Frequent Kick–Loss Conversion

Thirty-one oil and gas intervals (eight of which are major producing intervals) have been identified in the Sichuan Basin from the Quaternary down to the Sinian, and the pressure origins and present-day states of the upper and lower sequences differ significantly.

Abnormal high pressure is locally developed in the Zhenzhuchong–Leikoupo intervals, while the Jialingjiang–Qiongzhusi intervals are generally under high pressure. In contrast, the Dengying Formation underwent long-term exposure and meteoric water dissolution after deposition, resulting in a well-developed and highly connected fracture–vug system that presently behaves as a low-pressure, loss-prone interval. This "high above, low below" configuration forces a single openhole interval to confront the contradiction of hosting both high-pressure and low-pressure zones.

Measured pressure coefficients confirm this assessment: 1.10 in Well Gaoshi 1, 1.17 in Well Gaoke 1, 1.08 in Well Pengshen 3, 1.06 in Well Pengtan 306 and 0.97 in Well Datan 1, whereas Well Penglai 6 reaches 2.22, giving a vertical range exceeding 1.2. Such a large jump in pressure coefficient over a short vertical distance directly compresses the usable drilling fluid density interval, so that a single density value selected by conventional methods usually satisfies one constraint only at the expense of another.

Loss statistics further reveal the severity of the problem (Table 1). Well Gaoshi 6 lost 3 601 m³ of fluid at a density of 1.33 g/cm³, Well Gaoshi 12 lost 2 248 m³ at 1.27 g/cm³, and Well Pengshen 1 lost 1 155.4 m³; single-well losses reach the order of thousands of cubic meters. Gas shows were equally active over the same period (Well Anping 1, $\rho = 1.92$; Well Pengshen 3, $\rho = 2.15$; Well Dashen 001-X1, $\rho = 1.38$; Well Dashen 001-X3, $\rho = 1.75$). Loss and kick alternate along the time axis, forming a typical "coexistence of kick and lost circulation" pattern that is far more difficult to handle than a single type of downhole complication. Practice in the Penglai gas area indicates that this type of problem has become the primary factor restricting ROP improvement in the block[10]; statistics from the Moxi–Longnüsi block lead to a similar conclusion[11].

Table 1 Statistics of drilling fluid losses in selected Dengying Formation wells

Well	Mud density / (g·cm ⁻³)	Loss / m ³	Well	Mud density / (g·cm ⁻³)	Loss / m ³
Gaoshi 6	1.33	3 601	Moxi 22	1.29	245.5
Gaoshi 7	1.30	700.6	Gaoshi 103	1.25	125.3
Gaoshi 8	1.30	250.9	Pengshen 1	1.30	1 155.4
Gaoshi 9	1.37	709.0	Pengtan 306	1.45	93.8
Gaoshi 11	1.42	41.4	Pengshen 3	1.55	9.3
Gaoshi 12	1.27	2 248.0	Datan 1	1.25	2.1

It is worth noting that the loss volumes in Table 1 do not vary monotonically with mud density: Well Pengtan 306 lost only 93.8 m³ at a density of 1.45 g/cm³, whereas Well Gaoshi 6 lost 3 601 m³ at the lower density of 1.33 g/cm³. This indicates that the dominant control on lost circulation is not density itself but the scale and connectivity of the fractures and vugs encountered—that is, "geological factors dominate while engineering parameters act as triggers". Therefore, the technical focus of loss prevention and control should shift from simply controlling density to actively sealing fractures and vugs and actively raising the pressure-bearing capacity of the formation.

2.2 Strong Rock Abrasiveness and Low Rock-Breaking Efficiency

The drillability grade of sedimentary rocks in central Sichuan is generally 8–10, with some intervals not lower than grade 7. The mechanisms making each sequence difficult to drill differ and therefore require differentiated treatment.

The Triassic Xujiahe Formation consists mainly of sandstone interbedded with mudstone and shale, with high quartz content and strong abrasiveness, so that bit cutters wear rapidly. In Well Pengshen 2, six PDC bits achieved an average footage per bit of only 87.9 m and an ROP of 1.33 m/h. Permian limestone and shale commonly contain chert nodules, and local hard interbeds subject the cutters to impact loading; in Well Gaoshi 1, a single roller cone bit averaged 43.7 m of footage at an ROP of 1.34 m/h. The Ordovician–Cambrian strata are geologically old, highly compacted and exhibit a degree of plasticity, resulting in low utilization of rock-breaking energy; in the Canglangpu Formation of Well Pengshen 2, average footage per bit was 35.8 m at an ROP of 0.73 m/h. The Sinian Dengying Formation comprises dolomite and brecciated dolomite rich in ultra-hard minerals such as quartz, causing particularly severe bit wear; Well Gaoshi 1 recorded an ROP of 1.99 m/h with an average bit life of only 39 h.

Taken together, the Longtan, Gaotai and Canglangpu intervals have average ROPs below 1 m/h and constitute the "bottleneck intervals" for whole-well ROP improvement. Their common features are high content of abrasive minerals, strong heterogeneity, and the presence of plastic or hard interbeds, under which the cutters of conventional PDC bits fail rapidly through the combined action of abrasion and impact. This implies that the selection of ROP improvement tools must address both "increasing rock-breaking energy input" and "suppressing stick–slip vibration"; optimizing weight on bit and rotary speed alone is unlikely to be effective.

2.3 Severe Temperature and Pressure Conditions Limiting Tool and Fluid Adaptability

Measured data (Table 2) show static temperatures of 152–159 °C in the Dengying Formation of the Gaoshiti–Moxi block, 154–163 °C in the 2nd member of the Dengying Formation in the Penglai gas area, and 152.07 °C in the 4th member and 156.74 °C in the 2nd member in the Daxingchang structure. The average formation temperature of the blocks is about 155 °C with a maximum of 163 °C, and the corresponding formation pressure is 80–120 MPa.

Table 2 Statistics of drilling fluid losses in selected Dengying Formation wells

Block	Well	Interval	TVD / m	Static formation temperature / °C
Gaoshiti–Moxi	Gaoshi 1	Lower Deng-4	5 162.10	153.28
Gaoshiti–Moxi	Moxi 10	Dengying Fm	5 246.04	158.90
Gaoshiti–Moxi	Moxi 41	Upper Deng-4	5 199.57	153.08
Penglai gas area	Pengtán 101	Deng-2 member	6 210	163.41
Penglai gas area	Pengtán 103	Deng-2 member	6 456	163.00
Penglai gas area	Pengtán 1	Deng-2 member	5 771.5	162.58
Daxingchang structure	Datan 1	Deng-2 member	6 126.38	156.74

The influence of temperature on the drilling system is comprehensive and nonlinear. For measurement and control tools, the failure rate of electronic components rises exponentially above 150 °C, while non-metallic sealing materials undergo compression set and hardening; seal failure often precedes circuit failure. For working fluids, polymer additives undergo main-chain scission or excessive cross-linking at high temperature, manifested as an abrupt drop or sharp rise in apparent viscosity, loss of filtration control and deterioration of settling stability. Oil-based systems have better thermal stability, but their emulsifiers and organophilic clays still face declining emulsion stability and barite sag after prolonged high-temperature aging. Liu Gonghui et al. pointed out that accurate acquisition and active regulation of wellbore temperature and pressure have become one of the core bottlenecks for safe drilling of ultra-deep and extra-deep wells[12].

2.4 Active Sour Gas Zones with a Narrow Well-Control Margin

From the Leikoupo Formation down to the Sinian, hydrogen sulfide is commonly present in the Gaoshiti–Moxi block, the Penglai gas field and the Daxingchang block, with some intervals classified as highly sour. Measured statistics are as follows: the Longwangmiao Formation reaches a maximum H₂S content of 89.62 g/m³ (Well Gaoshi 102); the Dengying Formation reaches 72.17 g/m³ (Well Pengshen 3); Well Gaoshi 001-H26 recorded 22.66 g/m³ in the Dengying Formation; and the 1st member of the Leikoupo Formation in Well Penglai 18 ranges from 22.5 to 44.24 g/m³.

The threat posed by H₂S is twofold. On the one hand, its extreme toxicity means that the consequences of surface release far exceed those of conventional natural gas, and loss of control directly endangers personnel and nearby residents. On the other hand, H₂S causes hydrogen-induced cracking and sulfide stress corrosion in drill strings and wellhead equipment, reducing their actual load-bearing capacity. At the same time, shut-in pressures are high when high-pressure gas flows are encountered—in Well Pengxing 101, the return flow rate continued to rise while the string was being worked, and casing pressure rose to 37 MPa shortly after shut-in, leaving an extremely limited time window for response. The Sichuan Basin has a dense surface population and environmentally sensitive conditions, so the social cost of well-control failure is far higher than in ordinary blocks; this dictates that well-control design must incorporate greater redundancy[13]. Li Jun et al. argued that well control for ultra-deep complex wells is shifting from "passive response" to "active prevention", and that intelligent early identification is the prerequisite for this transition[13].

2.5 Narrow Window, Large Temperature Difference and Small Clearance Compromising Cementing Integrity

Cementing in the Dengying Formation must cope with the simultaneous presence of five unfavorable conditions: (1) a narrow safety density window, generally not exceeding 0.1 g/cm³; (2) a large temperature difference between top and bottom, up to about 80 °C; (3) high mud density of 2.0–2.5 g/cm³; (4) a long single-stage cemented interval of 2 000–3 500 m; and (5) a narrow annular clearance of only 11–16 mm. These five are internally related: a

narrow window forces the use of high-density mud, which together with the long cemented interval raises the annular equivalent circulating density (ECD) and further compresses the window; the large temperature difference causes rapid thickening in the lower high-temperature section while the upper low-temperature section remains unset for a long time, making it difficult to unify the thickening profile; and the narrow clearance makes displacement efficiency extremely sensitive to flow rate and flow regime, so that any deviation readily produces channeling.

More intractably, the need to substantially reduce wellbore mud density before penetrating the target zone creates a micro-annulus at the cement sheath–casing interface, which becomes a pathway for later gas channeling. In the first round of seven exploratory wells, the average excellent-rate of the 4th-spud liner cementing quality was only 21.3% and the qualification rate 37.6%, with gas channeling at the liner top commonly observed, directly affecting the 5th-spud operation and the long-term sealing integrity of the wellbore.

3 Key Drilling Technology System for Dengying Formation Gas Reservoirs

3.1 Casing Program Optimization and Extension Technology

The casing program is the first line of defense against multiple pressure systems. Its core lies in "predicting accurately, expanding effectively and separating clearly"—that is, accurate pressure profile prediction, effective expansion of the safety window, and rational placement of intervals with different pressures in different spud sections.

(1) Accurate formation pressure prediction. The prediction method must be matched to lithology. For sand–mudstone formations, an improved variable-exponent Eaton method is adopted: in the conventional model the compaction exponent C is taken as the constant 0.914, which yields a relatively large deviation when calibrated against measured pressures in this area; by reconstructing the compaction exponent as a depth-dependent function and introducing an additional correction term, the agreement in the transition from moderate-shallow to deep intervals is significantly improved. For carbonate formations, the Bowers effective-stress method is used instead, because carbonate compaction is dominated by chemical cementation and pressure solution and does not satisfy the normal compaction assumption underlying the Eaton method; forcing its application would introduce systematic error. Li Wenzhe et al. compared the equivalent-depth method, the Eaton method and the effective-stress method for carbonate rocks in the Luzhou block, and showed that the effective-stress method gives an average error of 5.3%, clearly better than the 12.2% of the Eaton method[14]. On the basis of an accurate pressure profile, two window-expansion measures—pressure-controlled degassing and depressurization, and efficient pressurized lost-circulation control—increase the formation pressure-bearing capacity by 0.22 g/cm³, creating the conditions for establishing a usable safety density window.

(2) Safety-window expansion and borehole enlargement. Besides raising the inherent pressure-bearing capacity of the formation, reducing annular circulating pressure loss is another route to window expansion. The use of reaming-while-drilling tools and eccentric bits reduces ECD during both drilling and cementing, which both ensures smooth casing

running and improves displacement conditions and cement sheath quality. Feng Jin developed a "bent motor (with stabilizer) + stabilizer + eccentric micro-reamer" anti-sticking reaming-while-drilling bottomhole assembly, which reduced the average sticking loss time per well by 93% in trials in three wells in the Gaoshiti–Moxi structure of central Sichuan[15].

(3) Block-specific casing program finalization. In the Gaoshiti–Moxi block, two critical mandatory isolation points—the 3rd sub-member of the 2nd member of the Jialingjiang Formation and the top of the Dengying Formation—were identified during exploration and appraisal on the basis of the three-pressure profile, and a conventional four-spud casing program was finalized. In the development stage, to address the problems of fragmented Deng-4 reservoirs and frequent sticking in slim holes, the reservoir hole size was changed from 149.2 mm to 160 mm, fundamentally alleviating sticking caused by cavings, and a five-spud program was finalized for Deng-4 development wells. In the Shehong–Yanting area of the Penglai gas area, a non-standard six-spud program was designed during exploration and appraisal, and the 14¾" casing shoe was raised from the top of the Leikoupo Formation to the top of the Xujiahe Formation to avoid the large-size difficult interval; across ten wells this saved an average of 140 t of $\Phi 374.65$ mm casing per well and shortened the Xujiahe drilling time from an average of 45.68 d to 25.17 d. In the development stage, drawing on the Gaoshiti–Moxi experience, the reservoir hole size was likewise enlarged to 160 mm[16]. In the Daxingchang block, two mandatory isolation points—the top of the Leikoupo Formation and the top of the basalt—were determined at the initial exploration stage, and a non-standard six-spud program was optimized for Well Datan 1 targeting the Dengying Formation. In the subsequent appraisal and development stage, oil-based mud was used in the Shawan Formation to counter water-sensitive collapse, the Emeishan Basalt Formation was drilled through with reduced density, and the lower Maokou–Dengying interval was combined to achieve five-spud completion. It was demonstrated that not tie-back stringing the $\Phi 273.05$ mm intermediate casing saved 17 d, creating the 299 d drilling cycle record in Well Dashen 102, which is 311 d shorter than Well Datan 1.

The practice in all three blocks shows that a casing program is not a one-off design product but should be dynamically iterated as drilling knowledge accumulates; the determination of "mandatory isolation points" must consider not only pressure isolation requirements but also the technical and economic balance between casing cost and construction time.

3.2 Accurate Wellbore Pressure Control Technology

To address narrow density windows and the coexistence of kick and loss, MPD equipment has been developed for two extreme conditions—ultra-deep wells with high pressure-bearing requirements, and ultra-large hole sizes with high flow rates—and a complete set of fine MPD techniques covering the whole "drilling–logging–cementing–completion" process has been established.

(1) MPD technology for ultra-deep wells. The system has a pressure-bearing capacity of 35 MPa, a wellhead pressure control accuracy of ± 0.07 MPa, a throttle response time of less

than 1 s and a throttling capacity of 14 MPa, reaching the internationally advanced level overall. It has been applied in more than 300 wells in the Gaoshiti–Moxi block and the Penglai gas field, reducing mud loss by over 84% and complex loss time by over 81% year on year.

(2) Ultra-large-size, high-flow-rate MPD equipment. Large hole sizes and high flow rates in upper formations cause severe natural throttling in conventional MPD equipment because of bore restrictions, rendering back-pressure control meaningless. To this end, a large-bore rotating control device with a 680 mm main bore, a 230 mm central tube bore and a rated pressure of 7 MPa was developed, together with an automatic choke control system with a full bore of 130 mm and a pressure rating of 14 MPa, meeting the requirements of fine MPD in a $\Phi 660.4$ mm hole at a flow rate of 150 L/s. Compared with conventional products (Table 3), the three key indicators of bore diameter, pressure rating and applicable flow rate have all been substantially exceeded, and the equipment has been successfully deployed in Well Shendi Chuansi 1[8].

Table 3 Comparison of performance indicators of fine MPD equipment

Item	Indicator	Conventional product	Self-developed product
Rotating control device	Main bore	≤ 540 mm	680 mm
Rotating control device	Central tube bore	≤ 220 mm	230 mm
Automatic choke manifold	Bore	Manifold 103 mm, choke valve 80 mm	Full bore 130 mm
Automatic choke manifold	Rated pressure	10.5 MPa	14 MPa
Applicable scope	Hole size / flow rate	540 mm / 80 L/s	680 mm / 150 L/s

(3) "Micro-overbalance with micro-loss" fine MPD technique. The Dengying Formation in the Gaoshiti–Moxi block is a typical fractured–vuggy reservoir in which the loss zone and the kick zone lie in the same interval, and the safety density window is only 0.01–0.05 g/cm³, i.e. a near-zero window. Under such conditions, pursuing "absolutely no loss" is neither realistic nor necessary—forcibly suppressing losses generally means that the bottomhole pressure exceeds the formation pore pressure and induces a kick. A "micro-overbalance with micro-loss" control strategy was therefore proposed: the bottomhole pressure is allowed to be slightly higher than the pore pressure to create a small positive differential, while a continuous loss rate of 1–5 m³/h is tolerated, so that a "controllable small loss" is exchanged for a "certain absence of kick". With this approach, mud loss during drilling was reduced by 81% and complex time by 92.4% compared with earlier conventional wells.

3.3 Kick/Loss Early Warning and Treatment Technology

(1) Geology–engineering integrated early warning. Focusing on the four problems of "kick, loss, collapse and sticking", a three-stage working mode of pre-drilling risk assessment, while-drilling tracking analysis and post-drilling comprehensive evaluation was established. Before drilling, wellbore modeling is completed to identify fracture-developed intervals, abnormal pressure intervals, loss-prone intervals and gas-show horizons, providing a basis for bit selection, parameter matching and density selection. During drilling, integrated

seismic data are used for abnormal pressure warning and the causes of complications that have occurred are diagnosed. After drilling, multi-disciplinary parameter analysis and iterative updating of the velocity field feed the knowledge gained from the well back into the design of subsequent wells. This mode has been systematically verified in the drilling practice of complex ultra-deep wells in the Penglai gas area, with the rate of failures and complications and the well-control risk declining simultaneously[10].

(2) Early kick/loss monitoring and warning system. Surface monitoring has long been constrained by two shortcomings: insufficient accuracy and inadequate warning lead time. The root cause is that the conventional "pit level plus manual monitoring" approach has limited resolution for volume changes, while gas expansion during upward migration systematically delays the moment at which a kick is detected. A digital surface monitoring and warning system for drilling kick and loss was therefore developed, integrating four sensing units: a precise non-full-pipe return flow monitoring device (non-contact ultrasonic, range 1–150 L/s, accuracy 2% FS); an electronic pit-level monitoring device ("tension–displacement" scale, resolution 0.01 m³, error ± 0.1 m³); a continuous annulus level monitoring device (electromagnetic acoustic transmitter, range 20–1 500 m, error $\leq 2\%$ FS, minimum sampling interval 5 s); and an intelligent return tank monitoring device (ultrasonic plus thermal imaging recognition plus machine learning). On the software side, trend-line criteria, machine learning models and an LSTM network are fused to identify kick and loss. The system achieves a flow monitoring accuracy of ± 1 L/s for kick and loss and a volume recognition accuracy of ± 0.1 m³, provides warning 3–5 min in advance on average, and measures the annulus level with an error of less than 5%. It has been applied in more than 120 wells, with a missed-alarm rate of 0% and a false-alarm rate below 10%[17]. The intelligent early kick detection method based on engineering parameter trends proposed by Wang Biao et al. provided an important reference for the algorithm design of this system[17].

(3) Downhole multi-cycle bypass valve. Conventional lost-circulation treatment requires multiple trips, and the long static periods associated with switching between treatment and drilling constitute a risk in themselves. Downhole multi-cycle bypass valves rated at 175 °C and 200 °C were developed, enabling 5–7 lost-circulation treatments in a single run. The tools cover four sizes—4³/₄", 6³/₄", 8" and 9"—with tensile strengths of 3 660–13 460 kN. They have been applied in 72 wells, eliminating 42 lost-circulation trips and saving over 600 h, thereby significantly reducing exposure risk during condition transitions.

(4) Optimized loss prevention and control for the Dengying Formation. Focusing on four typical problems—encountering voids while drilling, rapid conversion between lost-circulation pills and bridging pills, tripping under dual-density lost circulation, and encountering large fractures—improvements were made in pre-formulated sealing pills, pre-formulated lost-circulation pills matched to the bottomhole assembly, optimization of the particle grading of bridging pills, and dedicated treatment technology for large fractures. An overall regional approach was formed: "active prevention—efficient treatment of losses while drilling—reinforced treatment of losses during tripping—dedicated treatment of special severe losses".

3.4 Ultra-High Temperature Drilling Fluid Technology

(1) Whole-well drilling fluid system. The system is configured according to the overall principle of "inhibition and anti-collapse in the upper section, contamination resistance and sealing in the middle section, and high-temperature stability in the lower section". For upper formations, a KCl polymer drilling fluid is used, emphasizing strong inhibition, strong encapsulation and environmental friendliness to address mudstone dispersion, bit balling, collapse of unconsolidated formations and cuttings transport in large holes. For middle formations, an organic-salt polysulfonate drilling fluid is used, emphasizing resistance to gypsum/salt contamination and acid gas contamination together with sealing and anti-collapse, to address gypsum beds, salt beds, fractured fault zones and H₂S/CO₂-bearing formations. For lower formations, high-temperature-resistant oil-based drilling fluid and JFS water-based drilling fluid are used, emphasizing high-temperature rheological stability, low filtration, strong lubrication and strong sealing, to address safe drilling in deep HTHP, loss-prone and collapse-prone formations and in slim-hole long horizontal sections[9][18].

(2) High-temperature-resistant, strongly sealing oil-based drilling fluid. The high-temperature stability of an oil-based system depends on the synergy of emulsifier, organophilic clay and fluid-loss additive; failure of any one of them triggers a chain reaction. Six series of additives were therefore developed—ultra-high-temperature emulsifier CQ-HOP, organophilic clay CQ-HOC, fluid-loss additive CQ-HOF, sealing agent CQ-HOY, rheology modifier CQ-HOR and shear-strength improver CQ-HOT—forming an oil-based drilling fluid system with a temperature resistance of 260 °C and a maximum density of 2.60 g/cm³ (Table 4). The system has an emulsion stability (ES) of ≥800 V, an HTHP static filtration of less than 5 mL and a dynamic filtration of ≤10 mL, and a settling stability period of ≥10 d; the maximum recorded field temperature was 210 °C at a depth of 10 578 m. Research by Tao Huaizhi et al. showed that this system was successfully applied in Well XA-1 in the Junggar Basin (depth 11 156 m, bottomhole 230 °C/230 MPa), filling the gap in domestic 260 °C grade ultra-high-temperature oil-based drilling fluid technology[19].

Table 4 Properties of the 260 °C oil-based drilling fluid system

Density / (g·cm ⁻³)	AV / (mPa·s)	PV / (mPa·s)	YP / Pa	Gel (initial/final) / Pa	ES / V	HTHP / (mL/mm)
1.80	58	47	11	2.0/4.0	915	4.8/1.5
2.40	86.5	71	15.5	2.5/5.5	846	3.2/1.5
2.60	126	107	19	3.5/7.0	1 037	4.4/1.5

As shown in Table 4, when the density is increased from 1.80 to 2.60 g/cm³, the plastic viscosity rises from 47 to 107 mPa·s, an increase of about 128%, while the ES remains above 846 V and the HTHP filtration does not deteriorate. This indicates that the system maintains good emulsion stability and filtration control even at high solids content—which is precisely the technical difficulty of ultra-high-temperature, high-density oil-based drilling fluids.

(3) Novel water-based drilling fluid system (JFS PLUS). The advantages of water-based systems lie in environmental performance and cost, while their weaknesses are inhibitive capacity and lubricity. On the basis of an instant-sealing anti-collapse drilling fluid system, film-forming sealing agents and encapsulated lubricants were selected and upgraded with solid–liquid synergistic lubrication and multi-component, multi-stage sealing technology, forming a multi-phase film-forming intelligent-lubrication water-based drilling fluid system. Its core mechanisms include three aspects:

① Film-forming sealing and pressure isolation. A dense polymer film formed by filtration on the borehole wall blocks the transfer of filtrate and pressure into the formation; elastically deformable materials are driven by differential pressure into pores and fractures where they deform and fill, raising the cementation strength of the near-wellbore formation.

② Intercalation inhibition. Intercalation completely suppresses surface hydration of clay minerals, and 8%–10% KCl is added to increase salinity, weakening the hydration driving force from the perspective of chemical potential.

③ Targeted lubrication. At the instant of bit shearing, the encapsulated structure is destroyed and a high-concentration lubricant is released directionally, achieving targeted cooling and lubrication together with drag reduction and anti-backing-off.

Cuttings rolling recovery evaluation (Table 5) shows that JFS PLUS achieves a first-cycle recovery of 98.56% and a second-cycle recovery of 98.24%, significantly better than the 15.90% and 8.55% of fresh water and also better than the 89.12% and 91.72% of the original JFS system. The closeness of the second-cycle and first-cycle recoveries indicates that the inhibitive film is durable rather than consumed in a single pass. The system was trial-applied in nine wells in Gaoshiti–Moxi, shortening the horizontal-section drilling cycle by 35.03% compared with oil-based fluid.

Table 5 Inhibition evaluation (cuttings rolling recovery)

System	First-cycle mass recovered / g	First-cycle recovery / %	Second-cycle mass recovered / g	Second-cycle recovery / %
Fresh water	7.95	15.90	0.68	8.55
JFS	44.56	89.12	40.87	91.72
Multi-phase film-forming intelligent lubrication (JFS PLUS)	47.28	98.56	46.22	98.24

3.5 Efficient Rock-Breaking Tools and Techniques for ROP Improvement

(1) Customized bits. Software for rock mechanical characterization and three-dimensional bit design was developed, enabling customization of bits from 3½" to 32", and four series of "Chuanqing" customized bits were established: the A series (conventional PDC, for soft to medium-hard formations), the M series (roller-cone/PDC hybrid bit, for strongly heterogeneous difficult formations), the H series (PDC bit for difficult formations, for poor drillability, high abrasiveness and heterogeneity) and the F series (PDC bit dedicated to shale).

In applications in the Gaoshiti–Moxi and Penglai blocks of the Sichuan Basin, a single bit achieved over 300 m of footage in the Dengying Formation at an average ROP of 5.5 m/h, an increase of 13% over offset wells. Block records include a 668.89 m "one-run" in the $\Phi 333.4$ mm Ziliujing Formation in the Penglai block, a 422.8 m "one-run" in the $\Phi 311.2$ mm Xujahe Formation in the Gaoshiti–Moxi block, a maximum ROP of 5.16 m/h in the $\Phi 215.9$ mm Longtan–Maokou interval, and a maximum daily footage of 272 m with $\Phi 241.3$ mm bits in a highly sour area. Research by Wang Yao et al. on the bit rock-breaking mechanism in the dolomite formations of the Penglai gas area provided a theoretical basis for customized bit design[20].

(2) All-metal torsional impact hammer. Stick–slip vibration of PDC bits in hard formations is the direct cause of cutter chipping and reduced ROP. The role of the torsional impact hammer is to superimpose high-frequency circumferential impact on rotary shear so that the rock-breaking mode changes from shear-dominated to impact-fracture-dominated. After overcoming the torsional impact driving mechanism and erosion resistance problems, the material was upgraded from 4145H to 4330V with the addition of a hardbanding design, forming the CQNC-209, CQNC-254 and CQNC-330 product series with frequencies of 700–2 400 cycles/min, impact torques of 800–1 200 N·m, body tensile strengths of 300–640 t and torsional strengths of 140–360 kN·m. Typical application data: Well Gaoshi 137-H5, 459 m of footage in the Xujahe–Leikoupo interval at an ROP of 4.56 m/h; Well Gaoshi 009-H37, 541.66 m in the Meitan–Canglangpu interval at 2.83 m/h; Well Pengyang 001-H1, 318 m in the Xu-6 to Xu-4 intervals at 3.12 m/h.

(3) Rotary steerable system. The deep build-up sections in the Gaoshiti–Moxi block have long suffered from backing-off during sliding orientation, low ROP and difficult landing, the root cause being high friction and degraded weight transfer efficiency during sliding. The self-developed CG STEER-675 rotary steerable system eliminates sliding conditions through continuous rotation. It was trialed and then applied in 11 wells with a cumulative footage of 6 806 m, increasing ROP by over 60% and setting a record maximum TVD of 5 125 m. At the same time, reaming time was reduced by 27%–92.23% and reaming intervals shortened by 41%–95%, with borehole quality significantly improved.

(4) Real-time drilling parameter optimization. The key to parameter optimization is that the model must be updated while drilling, because formation changes quickly invalidate any fixed parameter combination. A drilling parameter adaptive and real-time optimization system was developed, introducing machine learning algorithms to rapidly train a relationship model between ROP and parameters such as weight on bit and rotary speed from large volumes of real-time drilling data, while comprehensively considering the constraints imposed by stick–slip vibration, drillstring buckling and hole cleaning. The system calculates and pushes optimized parameter combinations in real time, helping to raise the average ROP in formations such as the Xujahe by over 20%[21].

(5) Underbalanced drilling technology. Gas-phase, liquid-phase and gas–liquid two-phase underbalanced drilling technologies have been developed, comprising five principal techniques: liquid, dry gas, mist, foam and aerated drilling. They have been applied in over 2 000 wells across 17 oil and gas areas in China including Sichuan, Xinjiang, Qinghai and

Puguang, increasing ROP by up to a factor of ten compared with conventional drilling. Multiple domestic records have been set and maintained: maximum daily footage in gas drilling, 680 m (Well LG39); longest single-run footage with an air hammer, 1 951 m (Well LG001-31); longest single-well gas drilling footage, 3 604.33 m (Well LG26); deepest nitrogen drilling, 6 200 m (Well MD2); longest horizontal section drilled with nitrogen, 602.26 m (Well GA2H8-2); and maximum ROP in gas drilling, 36.6 m/h (Well L17).

3.6 Efficient Measurement and Logging While Drilling Technology

(1) High-flow-rate vertical MWD inclination tool. Large hole sizes require high flow rates for cuttings transport, but increasing the flow rate intensifies erosion of the valve assembly of MWD tools; the two requirements have long constrained each other. By overcoming key technologies such as large-flow-path erosion-resistant valve design and adopting a cemented carbide valve body, a high-flow-rate vertical MWD inclination tool was developed, raising the limiting operating flow rate by 70% compared with existing tools, with a flow range of 40–120 L/s and a transmission accuracy above 98%. It was applied in more than 60 runs in the 3rd to 5th spuds of Well Shendi Chuansi 1 (hole sizes $\Phi 593.73/444.5/323.85$ mm, interval 801–9 506 m, flow rate 40–120 L/s) with a maximum single-run circulating time of 299.5 h, and has been extended to over 80 wells in the Sichuan–Chongqing and Xinjiang areas.

(2) 185 °C/200 °C high-temperature MWD systems. A 185 °C/206 MPa high-temperature MWD tool was developed with dynamic inclination accuracy of $\pm 0.5^\circ$, static inclination accuracy of $\pm 0.1^\circ$, azimuth accuracy of $\pm 1^\circ$, a transmission rate of 1–2 bps and a battery life of ≥ 200 h. It has been applied in over 50 wells, with a maximum circulating temperature of 172 °C, a measurement depth exceeding 8 400 m, a maximum pressure of 182 MPa and a maximum operating time of 298 h. The 200 °C ultra-high-temperature MWD tool adopts an ultra-high-temperature multi-chip module (almost no change after baking at 200 °C for 200 h) and has been applied in over 10 wells in the Sichuan–Chongqing and Xinjiang areas, with a maximum application depth of 9 900 m and a maximum circulating temperature of 176 °C. Typical applications include Well Xinyuan 302 (152.4 mm hole, interval 8 256–8 422 m, static temperature 188 °C, circulating temperature 172 °C) and Well Moxi 019-H5 (149.2 mm, 6 537–6 972 m, static 175 °C, circulating 167 °C).

(3) Resistivity-while-drilling tool. In central Sichuan, the high temperature and strong vibration in the Dengying Formation cause high failure rates and low operating efficiency of resistivity-while-drilling tools. The Chuanqing Type 475 (4 $\frac{3}{4}$ ") resistivity-while-drilling tool was developed for 142–165 mm holes, with temperature resistance of 175 °C, pressure resistance of 140 MPa, a resistivity range of 0.05–4 000 $\Omega \cdot \text{m}$, a four-quadrant azimuthal gamma ray (range 0–600 API), transmission frequencies of 2 MHz and 400 kHz (frequency error $\pm 0.1\%$), and an endurance of ≥ 200 h per run; it can be interfaced with the self-developed ultra-high-temperature MWD.

3.7 Ultra-Deep Liner Cementing Technology

(1) Automatic managed-pressure cementing. Wellbore pressure changes dynamically during cementing, and manual adjustment cannot keep pace with condition transitions. Based on real-time data acquisition, dynamic annular pressure calculation, casing pressure control recommendations and the linkage between casing pressure commands and the control system, the system achieves visual simulation monitoring, quantitative annular pressure analysis, real-time ECD calculation and managed-pressure value push, and servo-motor-linked choke control. The system response time is under 10 s and the pressure control accuracy reaches 0.1 MPa. The technology has been extended from the Gaoshiti–Moxi block to the Sichuan–Chongqing area with over 200 field applications, realizing automatic pressure control throughout cementing and increasing the average cementing qualification rate by 25%.

(2) High-strength, high-toughness anti-channeling cement slurry. The inherent brittleness of conventional set cement means that micro-cracks readily develop under later changes in conditions (pressure testing, stimulation, temperature and pressure cycling), which is the root cause of gas channeling at the liner top and sustained annular pressure. A high-strength, high-toughness anti-channeling cement slurry system was therefore developed, centered on fine mineral reinforcing materials and polymer plasticizing and toughening materials, and supported by expansion and toughening materials, a close-packing design and high-temperature, large-temperature-difference additives (resistant to a temperature difference above 110 °C). It has a density of 1.90–2.50 g/cm³, a 7 d compressive strength exceeding 25 MPa, an elastic modulus of 4–6 GPa, a Poisson's ratio of 0.155–0.193 and a linear expansion rate of 0.06%–0.08%. Laboratory evaluation shows an external load resistance of 50 MPa, 43% higher than conventional cement slurry (Table 6). Its anti-channeling mechanism is twofold: on the one hand, material expansion compensates for cement hydration shrinkage and eliminates interfacial micro-annuli; on the other hand, reducing the elastic modulus achieves toughening so that the cement sheath releases energy through deformation rather than cracking under stress. It has been applied in over 500 wells in the Sichuan–Chongqing area[22].

Table 6 Properties of the high-strength, high-toughness anti-channeling cement slurry

Density / (g·cm ⁻³)	Poisson's ratio	7 d Young's modulus / GPa	7 d compressive strength / MPa	7 d tensile strength / MPa	7 d linear expansion / %
1.90	0.193	5.89	34.0	3.50	0.06
2.10	0.183	4.33	26.5	3.32	0.08
2.20	0.155	3.20	25.9	2.50	0.06

(3) Ultra-high-temperature cement slurry. Under ultra-high-temperature conditions, cement slurry faces three difficulties: sharply shortened thickening time, additive failure and strength retrogression. Five key additives, including an ultra-high-temperature suspension stabilizer and a high-temperature strength stabilizer, were developed, forming a cement slurry system resistant to 220 °C. Performance evaluation (Table 7) shows a top-to-bottom density difference of <0.02 g/cm³, zero free fluid, fluid loss of <50 mL, adjustable thickening time and a transition time of 2–3 min; the 2 d and 30 d compressive strengths of the set cement both exceed 30 MPa with no long-term strength retrogression. It has been applied in over 50

wells with a maximum temperature of 196 °C. The fact that the 2 d and 30 d strengths are essentially equal indicates that the system does not undergo late strength retrogression at high temperature, which is particularly important for ensuring long-term sealing integrity.

Table 7 Properties of the ultra-high-temperature cement slurry

BHCT / °C	Fluidity / cm	High- temp rheology (n, k)	Top– bottom density difference / (g·cm ⁻³)	Free fluid / %	Fluid loss / mL	Thickening time / min	2 d compressive strength / MPa	30 d compressive strength / MPa
200	22	0.70, 1.83	0.02	0	36	383	30.4	32.4
210	21	0.71, 1.63	0.02	0	32	402	32.8	33.5
220	21	0.73, 1.60	0.02	0	38	372	31.3	32.1

(4) Liner hanger series. For conditions of lost circulation when pumping and back-flow when stopping, a packer-type liner hanger was developed; the 70 MPa series has an overall tensile strength of $\geq 3\ 000$ kN, collapse resistance of 60 MPa, internal pressure resistance of 70 MPa and a packer isolation pressure of 70 MPa, reversing the long-standing dependence on imports for such products, with over 300 field applications. To address the low hanging reliability and insufficient sealing pressure of ultra-large-size heavy-duty liners, a 486 mm $\times$ 362 mm high-pressure heavy-duty liner hanger was developed, with a hanging load of 650 t, a tensile strength of 1 000 t, a sealing pressure of 65 MPa and a setting initiation pressure of 0.6 MPa; it was successfully applied in Well Shendi Chuansi 1, filling an international technology gap.

3.8 High-Strength Coring Tools and Digital Empowerment

(1) High-strength coring tools. Coring in ultra-deep wells faces three difficulties: insufficient tool strength reserve, difficulty in gripping the core and core fragility. A high-strength coring tool was developed with tensile and torsional strengths 1.4 and 2.0 times those of conventional coring tools respectively, together with active core gripping, core-blocking warning and automatic blocking-release technologies. It has been used for coring in 36 ultra-deep wells of the 8 000 m class in the field, with a maximum coring depth of 10 786.66 m and a maximum temperature of 212.8 °C; a recovery of 100% was achieved in many wells, ensuring complete and accurate acquisition of geological data from ultra-deep strata[23].

(2) Digital empowerment. Focusing on drilling and completion operations and on "unified acquisition, unified transmission and unified application", 235 digital operation sites have been built, enabling the acquisition of more than 1 300 data items in 21 categories together with intelligent decision support, reducing the kick/loss time ratio by 10.3% year on year with a warning accuracy of 95%. Based on intelligent drilling decision and control technology integrating "expert experience + theoretical models + big data analysis models", 16 algorithm models have been developed covering parameter optimization, downhole friction and torque analysis, trajectory design and anti-collision analysis, and 36 software products—including intelligent warning, dynamic simulation, a digital well-kill system and

an EISC well-control emergency system—together with 33 hardware products such as electronic pit-level monitors and non-full-pipe flow monitors have been developed. For a 5 000 m well, the error between the theoretical and actual fill/return volumes monitored by the tripping system can be controlled within 0.5 m³. The concept of "specialized management for construction, project management for operations" was introduced, and a production mode of "engineering operation intelligent support system + EISC remote technical support + digital project department" was established, helping to increase the ROP of deep and ultra-deep wells by over 15%[24].

(3) Well-control safety system. In response to the well-control risk characteristics of "three highs and one ultra", main well-control equipment such as high-pressure, high-sour-resistant and large-bore blowout preventers was customized (70 MPa, HH/EE-NL sour service grade; UNS N06625 weld overlay applied to 40 cm at both ends of BOP manifold lines and to the ring groove; full-channel UNS N06625 overlay on the choke and kill manifold). Self-cleaning gas–liquid separators, erosion-resistant elbows and other accessories have been widely adopted, and an H₂S monitoring "sentry system" is deployed. Eight kick prevention and control techniques including "Eliminating Kick During Tripping" were developed; the CNPC standard Q/SY 02876 *Specification for Well-Control Monitoring During Drilling* was led in drafting; and *Technical Specification for Safe Drilling of Ultra-Deep Slim Holes in the Sichuan–Chongqing Area* and *Well-Control Requirements for Dual-Density Drilling Operations* were formulated, integrating digitalization into well-control management, kick prevention and key risk control. In the Sichuan–Chongqing area, eight emergency drilling fluid reserve stations (with reserves exceeding 6 000 m³) and seven barite powder warehouses (1.1 × 10⁴ t) have been built, 37 emergency vehicles deployed and 550 t of emergency cement stockpiled, establishing a "materials + equipment + vehicles" two-hour comprehensive emergency support circle. A well-control emergency rescue technology centered on "information-based decision and command + twin-controlled robot group" has been developed[13].

4 Field Application: Drilling Program for the Pengshan–Qingshen Block

4.1 Offset Well Data and Risk Analysis

The Pengshan–Qingshen block is a new area with a low degree of exploration, and because drilling data for the block itself are lacking, offset well analysis becomes the primary means of risk identification. The offset Well Leshan 1 was completed in April 2020 at a total depth of 5 639 m, with the Maidiping Formation as the completion interval and the Qiongzhusi Formation as the target, a drilling cycle of 294.63 d and an average ROP of 3.01 m/h. The complications encountered were as follows:

1. Collapse and sticking in the Ziliujing Formation: drilling to 3 031.82 m with mud of density 1.65 g/cm³; obstruction was encountered at 2 500.38 m during tripping; normal conditions were restored after reaming and heavy-slug sand lifting, at a cost of 1.47 d.

2. Lost circulation in the 3rd member of the Leikoupo Formation: lost circulation occurred at 3 724.17 m with mud of density 1.83 g/cm³; circulation losses ceased naturally, at a cost of 3.03 d and 29.9 m³ of drilling fluid.

3. Kick in the Maokou Formation: a kick occurred at 5 020.17 m (4th member of the Maokou Formation) with mud of density 1.80 g/cm³; the pit level rose by 0.6 m³ and the well was shut in immediately, with a shut-in drill pipe pressure of 12 MPa and casing pressure of 22.6 MPa; circulation was restored after the density was raised to 2.20 g/cm³ and the well was circulated through the choke. Because the design pressure coefficient was only 1.2, managed pressure was used to reduce the density to 1.70 g/cm³ to release formation pressure, at a cost of 22.56 d (test production 2.12×10^4 m³/d).

4. Lost circulation in the Qixia Formation: lost circulation occurred at 5 305 m in the 2nd member of the Qixia Formation with mud of density 1.90 g/cm³; losses stopped after adding a lost-circulation material while drilling, but recurred when drilling continued to 5 313.20 m, with a cumulative loss of 143.4 m³.

The above data lead to three conclusions. First, the Ziliujing Formation has poor borehole stability and is prone to collapse and sticking. Second, the Maokou Formation contains abnormal high pressure not foreseen in the design, with a pressure coefficient far exceeding the design value of 1.2. Third, the 3rd member of the Leikoupo Formation and the Qixia Formation are prone to losses under high-density drilling fluid. In the third complication, the "raise density to kill—then reduce density to release" process took 22.56 d, accounting for the main part of the whole-well complex loss time; its essence was insufficient understanding of Maokou Formation pressure at the design stage. This suggests that in the design of new areas, adjustable casing program margin must be reserved for uncertainty in pressure prediction.

4.2 Casing Program Design

A five-spud program with a six-spud alternative was preliminarily designed, using a $\Phi 660.4$ mm bit to spud and a $\Phi 190.5$ mm bit to reach total depth, with $\Phi 168.28$ mm casing run for completion. To address the unknown risks arising from the low exploration maturity of the Dengying Formation, a $\Phi 139.7$ mm slim hole is reserved as an alternative.

- 1st spud: drill with a $\Phi 660.4$ mm bit to about 150 m and run $\Phi 508$ mm casing.
- 2nd spud: drill with a $\Phi 444.5$ mm bit to the top of the Shaximiao Formation and run $\Phi 365.13$ mm casing to isolate upper loss and collapse intervals and to install the wellhead.
- 3rd spud: drill with a $\Phi 333.4$ mm bit to the top of the 3rd member of the Jialingjiang Formation and run $\Phi 273.05$ mm casing to isolate upper loss and collapse intervals and gypsum/salt formations, creating conditions for drilling the lower high-pressure formations.
- 4th spud: drill with a $\Phi 241.3$ mm bit to the top of the Qixia Formation and hang $\Phi 219.08$ mm casing to isolate the abnormal high-pressure Maokou Formation.
- 5th spud: drill with a $\Phi 190.5$ mm bit to total depth in the Dengying Formation, hang and tie back $\Phi 184.15$ mm + $\Phi 177.8$ mm + $\Phi 168.28$ mm casing for completion.

- Alternative: if severe lost circulation occurs in the Dengying Formation preventing further drilling, $\Phi 168.28$ mm production casing can be hung in advance at the top of the Dengying Formation, and the 5th spud can be completed with a $\Phi 139.7$ mm bit before hanging a $\Phi 114.3$ mm liner.

The design logic of this program is "placing high-pressure and low-pressure intervals in different spuds": the upper collapse and loss intervals, the middle gypsum/salt interval, the abnormal high-pressure Maokou Formation and the low-pressure fractured–vuggy Dengying Formation are isolated in separate sections, avoiding the coexistence of different pressure systems within the same openhole and weakening the physical basis for simultaneous kick and loss at the source. The reserved slim hole provides a fallback for unknown risks in the Dengying Formation—if an untreatable severe loss is encountered in the 5th spud, casing can be run early to isolate the zone and operations continued in a slim hole, avoiding abandonment of the entire well. This approach is consistent with the orientation of casing program optimization in the Penglai gas area[25].

4.3 ROP Improvement Technique and Bit/Parameter Design

The ROP improvement technique is designed around "high-efficiency PDC + high-torque motor + fine managed pressure". For the Quaternary to the top of the Suining Formation, the Suining to Ziliujing interval, the strongly abrasive Xujiache interval and the Leikoupo–Jialingjiang interval, "high-efficiency PDC/hybrid bit + high-torque motor" is adopted. For the Jialingjiang–Dengying interval, where multiple pressure systems and the coexistence of kick and loss are expected, fine MPD is designed together with "high-efficiency PDC/hybrid bit + fine managed pressure". The bit selection and drilling parameter design are shown in Table 8.

Table 8 Bit selection and drilling parameter design

Hole size / mm	Interval	Bit model	WOB / kN	Rotary speed / (r·min ⁻¹)	Flow rate / (L·s ⁻¹)	Standpipe pressure / MPa
660.4	Quaternary	GS1905, 535G	40–160	40–80	35–75	5–15
444.5	Quaternary– top Suining	TS516, CAS5193D, GS1605T	100–180	50–80	≥75	20–30
333.4	Suining– Ziliujing	CAS5163D, TS516, WS505, GS1635T	120–200	60–90	≥45	20–30
333.4	Xujiache Formation	CAS6163D, STR616, STR716ZX, KPM1633DST	160–250	60–80	≥45	30–35
333.4	Leikoupo– Jialingjiang	TS516, WS505, CAS5163D, GS1635T	120–200	60–90	≥45	30–35
241.3	Jialingjiang– Shawan	TS616, ST616ZX,	120–180	50–60	≥28	≥35

		CAS6163D, KPM1642RT				
241.3	Emeishan Basalt Fm	TS616, T713DM, STR616ZX, CAS7134D	120–180	50–60	≥ 28	≥ 35
241.3	Maokou–top Qixia	CAS6163D, STR616ZX, TS616, KPM1642RT	120–180	50–60	≥ 28	≥ 35
190.5	Qixia– Qiongzhusi	TS616, CAS5163D, STR616ZX	50–120	60–90	20–25	25–35
190.5	Maidiping– Dengying	CAS5164DA, GS1306T, BF613, BF713	50–120	60–90	20–25	25–35

As shown in Table 8, the weight on bit for the strongly abrasive Xujiahe interval (160–250 kN) is significantly higher than for adjacent intervals; this is a targeted configuration for strong abrasiveness and high rock-breaking energy demand. After entering the 190.5 mm slim hole, the weight on bit drops to 50–120 kN and the flow rate to 20–25 L/s, constrained by both drillstring strength and hydraulic power.

4.4 Drilling Fluid, BHA and Cementing Design

(1) Drilling fluid design. The system is configured according to interval-specific problems. For the 1st spud, with channeling losses and collapse in the Quaternary surface interval, a high-viscosity bentonite drilling fluid is used for fast drilling and a viscous pill for hole cleaning. For the 2nd spud, with a large hole from the Quaternary to the top of the Suining Formation and hydration-prone red-bed mudstone, a KCl polymer drilling fluid is used. For the 3rd spud, from the Suining to the Xujiahe Formation (thick, containing mudstone, shale and thin coal seams, prone to collapse), an organic-salt polymer drilling fluid is used, while from the Leikoupo Formation to the top of the 3rd member of the Jialingjiang Formation, where long gypsum/salt beds and brine-bearing formations may be encountered, an under-saturated brine drilling fluid is used. For the 4th spud, the under-saturated brine drilling fluid is continued from the 3rd to the 1st member of the Jialingjiang Formation, while an instant strong-sealing anti-collapse drilling fluid is used from the Feixianguan Formation to the top of the Qixia Formation (where the aluminous mudstone of the Shawan Formation is prone to hydration swelling and the Maokou Formation has developed fractures with coexisting gas, loss and collapse). For the 5th spud, from the Qixia to the Dengying Formation (where the Qiongzhusi shale shows frequent oil and gas, the Dengying Formation is low-pressure with poor borehole stability, and combining it with upper formations readily causes loss and loss-to-kick conversion), an instant strong-sealing anti-collapse drilling fluid is used.

(2) Bottomhole assembly design. Considering deviation control and vertical drilling, a double-stabilizer pendulum assembly is designed, with 11" drill collars and a vertical MWD

inclination tool for hole sizes of $\Phi 444.5$ mm and above. In loss-prone intervals, a multi-cycle bypass valve is added to the assembly to reduce trips and improve lost-circulation treatment efficiency. Each spud is equipped with a drilling jar and heavy-weight drill pipe, and the 4th and 5th spuds adopt a bypass valve plus jar combination to meet complex treatment requirements.

(3) Cementing design. The $\Phi 508$ mm surface casing uses the inner-string method with conventional-density cement slurry. The $\Phi 365.13$ mm intermediate casing 1 uses the inner-string/double-plug method with low-density plus conventional-density slurry. The $\Phi 273.05$ mm intermediate casing 2 uses the inner-string/double-plug method with a tough anti-gas-channeling slurry. The $\Phi 219.08$ mm hung intermediate casing 3 uses liner cementing with a high-temperature-resistant tough anti-gas-channeling slurry plus fine managed-pressure balanced cementing. The $\Phi 184.15$ mm + $\Phi 177.8$ mm + $\Phi 168.28$ mm production casing is cemented by hanging and tie-back, with the hung section using a double-setting, double-density, high-temperature-resistant tough anti-gas-channeling slurry plus fine managed-pressure balanced cementing, and the tie-back section using a tough anti-gas-channeling slurry. For large-size casing, the inner-string/double-plug cementing method is designed to improve displacement efficiency. For the hung intermediate casing and production casing, considering the multi-pressure-system character of the cemented interval, fine managed-pressure balanced cementing is designed to suppress gas channeling at the liner top and sustained annular pressure at the process level.

5 Conclusions

1. Drilling of the Dengying Formation gas reservoirs faces five major challenges: coexistence of kick and loss caused by vertically superimposed pressure systems; poor drillability due to strong rock abrasiveness; inadequate adaptability of tools and working fluids under high temperature and pressure; high well-control risk in sour gas zones; and difficulty in ensuring cementing quality with narrow windows, large temperature differences and small clearances. Their essence is a problem of wellbore pressure control and borehole stability under multi-field coupling, which requires a systematic solution with casing program optimization as the prerequisite, fine managed pressure as the core, and the temperature and pressure resistance of materials and equipment as the support. Loss statistics further show that lost-circulation volume does not vary monotonically with mud density; geological factors (scale and connectivity of fractures and vugs) play the dominant role while engineering parameters act as triggers. Therefore, the focus of loss prevention and control should shift from density control to active sealing and active improvement of pressure-bearing capacity.

2. The established formation pressure prediction method combining the improved variable-exponent Eaton method for sand–mudstone and the Bowers effective-stress method for carbonate rocks, together with fine managed-pressure degassing/depressurization and efficient pressurized lost-circulation control for window expansion (increasing formation pressure-bearing capacity by 0.22 g/cm^3), provides a quantitative basis for the design of "five-to-six spud conventional plus non-standard" casing programs. The two optimizations in the

Penglai gas area—raising the 14³/₄" casing shoe and enlarging the reservoir hole from 149.2 mm to 160 mm—saved 140 t of casing per well and shortened the Xujiache drilling time by 20.51 d respectively, verifying the technical and economic benefits of dynamic iterative optimization. A casing program should be treated as a dynamic design product that is continuously revised as drilling knowledge accumulates, rather than as a one-off result.

3. Accurate wellbore pressure control is the core of safe drilling in the Dengying Formation. The combined application of ultra-large-size, high-flow-rate MPD equipment (680 mm main bore, 150 L/s, control accuracy ± 0.07 MPa, response < 1 s) and the "micro-overbalance with micro-loss" technique (window 0.01–0.05 g/cm³, maintaining a loss rate of 1–5 m³/h) reduced mud loss in the Dengying Formation of the Gaoshiti–Moxi block by 81% and complex time by 92.4%, with the overall block loss down by over 84% year on year. The essence of the "micro-overbalance with micro-loss" strategy is to exchange a controllable small loss for a certain absence of kick; it is a rational choice for weighing kick and loss risks under near-zero window conditions.

4. Ultra-high-temperature working fluids and cementing materials are the foundation for wellbore integrity. The 260 °C/2.60 g/cm³ oil-based drilling fluid (ES ≥ 800 V, HTHP filtration < 5 mL) and the multi-phase film-forming intelligent-lubrication water-based system (second-cycle cuttings recovery 98.24%, horizontal-section cycle shortened by 35.03%) are complementary. The high-strength, high-toughness anti-channeling cement slurry (external load resistance 50 MPa, 43% higher than conventional) and the 220 °C ultra-high-temperature cement slurry (30 d strength > 30 MPa, no strength retrogression), combined with automatic managed-pressure cementing (response < 10 s, accuracy 0.1 MPa), increase the cementing qualification rate by 25%.

5. The program design for the Pengshan–Qingshen block, a new area with a low degree of exploration, shows that placing high- and low-pressure intervals in separate spuds with a "five-spud with six-spud alternative" program, improving ROP with "high-efficiency PDC + high-torque motor + fine managed pressure", addressing collapse and loss with a staged strong-sealing drilling fluid system, and ensuring sealing integrity with fine managed-pressure balanced cementing can achieve risk-controllable ROP improvement on the basis of an offset well with an average ROP of 3.01 m/h and a high proportion of complex loss time. This provides a replicable technical template for drilling in similar new areas. The lesson from the offset Well Leshan 1 is that the design of a new area must reserve adjustable structural margin for deviation in pressure prediction.

6. Recommended priorities for further research are: (1) integration of look-ahead-while-drilling and geosteering to improve the prediction accuracy of formation pressure and complex geological bodies in areas with a low degree of exploration; (2) low-cost, environmentally friendly water-based drilling fluid systems resistant to temperatures above 240 °C; (3) closed-loop adaptive wellbore pressure control based on digital twins; and (4) efficient rock breaking in ultra-deep slim holes and extended-reach capability for long horizontal sections.

References:

1. ZOU Caineng, LI Shixiang, XIONG Bo, et al. Connotation, pathway and significance of building China into an "energy powerhouse"[J]. *Petroleum Exploration and Development*, 2025, 52(2): 463-477 (in Chinese).
2. YANG Yueming, WEN Long, LUO Bing, et al. Hydrocarbon accumulation of Sinian natural gas reservoirs, Leshan–Longnusi paleohigh, Sichuan Basin, SW China[J]. *Petroleum Exploration and Development*, 2016, 43(2): 179-188 (in Chinese).
3. WANG Haige, HUANG Hongchun, JI Guodong, et al. Progress and challenges of drilling and completion technologies for deep, ultra-deep and horizontal wells of CNPC[J]. *China Petroleum Exploration*, 2023, 28(3): 1-11 (in Chinese).
4. WU Xianzhu, WAN Fulei, CHEN Zuo, et al. Drilling and completion technologies for deep carbonate rocks in the Sichuan Basin: practices and prospects[J]. *Natural Gas Industry*, 2020, 40(2): 97-105 (in Chinese).
5. HAN Liexiang. New progress of drilling and completion technologies for ultra-deep wells in the Sichuan–Chongqing area[J]. *Oil Drilling & Production Technology*, 2019, 41(5): 555-561 (in Chinese).
6. ZHOU Yingcao, GUO Qingfeng, CAI Xiao, et al. Research progress of precise managed pressure drilling technology and equipment[J]. *Drilling & Production Technology*, 2024, 47(4): 94-104 (in Chinese).
7. LIU Wei, FU Jiasheng, GUO Qingfeng, et al. Research progress and prospects of key technologies for intelligent managed pressure drilling[J]. *Petroleum Drilling Techniques*, 2024, 52(5): 42-50 (in Chinese).
8. LI Zhilin, SHU Tengfei, ZHOU Jinghong, et al. Development and application of a precise managed pressure drilling system for ultra-deep large-size wells[J]. *Drilling & Production Technology*, 2026, 49(3): 190-197 (in Chinese).
9. SUN Jinsheng, YANG Jingbin, BAI Yingrui, et al. Research progress and prospects of drilling fluid technology for deep and ultra-deep formations[J]. *Petroleum Exploration and Development*, 2024, 51(4): 889-898 (in Chinese).
10. WAN Fulei, CAO Xiaoli, ZHANG Yao, et al. Research and practice of drilling technology for complex ultra-deep wells in the Penglai gas area, central Sichuan[J]. *Drilling & Production Technology*, 2023, 46(6): 34-40 (in Chinese).
11. CHEN Lili, SHEN Xinyu, YANG Xinhao, et al. Efficient drilling practice and implications in the Moxi–Longnusi block[J]. *Drilling & Production Technology*, 2023, 46(6): 26-33 (in Chinese).
12. LIU Gonghui, YANG Hongwei, LIU Wei, et al. Review of wellbore temperature and pressure measurement and control technologies for ultra-deep and extra-deep wells[J]. *Drilling & Production Technology*, 2026, 49(3): 44-52 (in Chinese).
13. LI Jun, YANG Hongwei, LONG Zhenyu, et al. Progress and prospects of key intelligent well-control technologies for ultra-deep complex wells[J]. *Drilling & Production Technology*, 2026, 49(3): 53-66 (in Chinese).

14. LI Wenzhe, LUO Pingya, LI Yatian, et al. Comparison and application of pore pressure prediction methods for carbonate formations: a case study in Luzhou Block, Sichuan Basin[J]. *Energies*, 2025, 18(10): 2647.
15. FENG Jin. Application of a new anti-sticking reaming-while-drilling tool in the Gaoshiti–Moxi structure, central Sichuan[J]. *Natural Gas Exploration and Development*, 2024, 47(4): 119-125 (in Chinese).
16. LI Wenzhe, ZHANG Yi, HE Fei, et al. Key technologies for optimized-fast drilling of ultra-deep horizontal wells in the Penglai gas area[J]. *Natural Gas Exploration and Development*, 2026, 49(3): 84-92 (in Chinese).
17. WANG Biao, LI Jun, YANG Hongwei, et al. Intelligent early kick detection method based on variation trends of engineering parameters[J]. *Petroleum Drilling Techniques*, 2024, 52(5): 145-153 (in Chinese).
18. LIU Fengbao, SUN Jinsheng, WANG Jianhua. Current status and development trend of drilling fluid technology for deep and ultra-deep wells in China and abroad[J]. *Xinjiang Oil & Gas*, 2023, 19(2): 34-39 (in Chinese).
19. TAO Huaizhi, AI Jiawei, SUN Jinsheng, et al. Research and application of an ultra-high-temperature 260 °C oil-based drilling fluid system[J]. *Drilling & Production Technology*, 2026, 49(3): 206-214 (in Chinese).
20. WANG Yao, CAI Zhixiang, XIA Lianbin, et al. Bit rock-breaking mechanism in dolomite formations of the Penglai gas area[J]. *Drilling & Production Technology*, 2026, 49(2): 79-87 (in Chinese).
21. ZHAO Xiuwen, YIN Hu, LI Qian. Architecture of a digital twin system for adaptive control of drilling parameters[J]. *Petroleum Drilling Techniques*, 2024, 52(5): 163-170 (in Chinese).
22. YANG Hongqi, CHEN Huinian, DENG Tianan, et al. Anti-gas-channeling cementing technology with small liners for ultra-deep exploratory wells in the Yuanba gas field[J]. *Oil Drilling & Production Technology*, 2020, 42(5): 592-599 (in Chinese).
23. YANG Liuqing, LIU Bin, ZHANG Wei, et al. Application and understanding of the "Chuan-style" 10 000 m coring technology in Well Shendi Take 1[J]. *Drilling & Production Technology*, 2026, 49(3): 90-95 (in Chinese).
24. WANG Junze, LI Qian, YIN Hu. Architecture of an intelligent early warning system for drilling complex risks based on digital twin technology[J]. *Petroleum Drilling Techniques*, 2024, 52(5): 154-162 (in Chinese).
25. WANG Yao, QIAO Qingsong, FU Zhi, et al. Casing program optimization and ROP improvement technology for ultra-deep wells in the Penglai gas area[J]. *Journal of Chongqing University of Science and Technology (Natural Science Edition)*, 2025, 27(3): 48-56 (in Chinese).