Early Production Decline Characteristics Main Controlling Factors and Development Insights for Horizontal Wells in the Wuping Block of Yanchang Oilfield

Qiang Zang

Karamay Vocational & Technical College, Xinjiang, China

Abstract: To address the issues of "rapid and complex production decline" observed in horizontal wells within the ultra-low permeability reservoirs of Yanchang Oilfield, this paper takes a typical well in the Wuping Block (Well Wuping-1) as a case study. By integrating production data analysis with multi-fracture numerical simulation, the early decline characteristics were systematically investigated. The results indicate that: 1) the early decline follows a harmonic decline model ($R^2>0.96$), revealing a high initial decline rate post-fracturing. 2) Multi-fracture simulation demonstrates significant uneven production distribution, characterized by "shielding effects" and "dead oil zones" near the wellbore, with the main production contribution coming from fractures on both sides and distal fractures. 3) Comparison with the performance of adjacent wells clarifies that waterflooding effectiveness, water breakthrough risks, and capillary forces are key factors controlling the transition of decline patterns. Based on these findings, engineering recommendations for mitigating decline are proposed from three aspects: optimizing fracturing design, fine-tuning waterflooding management, and preventing water breakthrough. These insights provide guidance for efficient development of similar reservoirs.

Keywords: Horizontal Well; Production Decline; Harmonic Decline; Multi-Fracture Simulation; Shielding Effect; Water Breakthrough

1. Introduction

1.1 Research Background and Significance

The Yanchang Oilfield in the Ordos Basin is a typical ultra-low permeability lithologic reservoir in China, with average permeability generally below 1 mD. To enhance single-well productivity and recovery rates, horizontal well volumetric fracturing has become the primary development technology in this region. However, production practices reveal that horizontal wells commonly face the development challenge of "high initial production followed by rapid decline," with complex and variable decline patterns that severely impact the adjustment of development plans and economic evaluation. Therefore, accurately characterizing the early production decline behavior of horizontal wells and revealing its underlying mechanisms form the theoretical foundation for formulating scientific production stabilization measures and achieving efficient development of ultra-low permeability reservoirs.

Production decline analysis is a core tool for reservoir performance analysis and development effectiveness evaluation. The classical Arps decline models (Exponential, Hyperbolic, Harmonic) are well-established for conventional oil and gas reservoirs, but their applicability in ultra-low permeability fractured reservoirs is often challenged. This is primarily because the fundamental assumptions of these models— "boundary-dominated flow" and "unchanging flow regime"—are difficult to satisfy under the conditions of complex multi-fracture networks and dynamically changing flow phases [1].

1.2 Domestic and International Research Status

Research on production decline in horizontal wells within ultra-low permeability reservoirs has evolved from early empirical curve fitting to multidisciplinary dynamic analysis integrating geomechanics, flow mechanisms, and engineering parameters. Current research primarily focuses on the following three areas:

1.2.1 Evolution of decline models and deepening of physical mechanisms

To overcome the limitations of classical Arps models in unconventional reservoirs, researchers are dedicated to developing models with a

stronger physical foundation. Represented by the power-law exponential decline model proposed by Valkó and its extended models (e.g., the SEPD model), these models introduce time-dependent decline exponents, enabling more accurate characterization of fracture-dominated transient flow and early linear flow characteristics, thus finding widespread application in shale oil and gas [2]. The latest trend in model development involves further internalizing geological and engineering parameters to enhance their physical meaning and predictive capability. For instance, the research by Wang et al. directly couples reservoir stress sensitivity effects and oil-water two-phase flow into the decline analysis framework, allowing the model to reflect the impact of dynamic permeability decline in late production stages and changes in relative permeability on the production decline trajectory, significantly improving the reliability of mid- to long-term predictions [3]. Simultaneously, the fractional-order decline model proposed by Liu et al. utilizes fractional calculus to describe the non-Darcy flow and "memory effect" of fluids in ultra-low permeability porous media, providing a new mathematical characterization tool for nonlinear decline under complex fracture networks [4]. These advances signify that decline analysis is shifting from purely mathematical fitting to mechanism-driven dynamic prediction.

1.2.2 Dynamic simulation of fracture heterogeneity and interference

Mechanisms the production contribution of the multi-fracture system formed by fracturing is highly uneven. The "stress shadowing effect" between fractures is the direct engineering cause of low reservoir utilization and rapid decline. Early research primarily analyzed interference between idealized fractures based on analytical models or simplified numerical models. The current research frontier has shifted towards quantitative evaluation and dynamic evolution simulation. Liu et al. established quantitative charts linking the degree of fracture interference with cluster spacing and fracture length by integrating geostatistics and flow simulation, providing direct guidance for optimizing fracturing design [5]. More cutting-edge research employs dynamic simulation methods coupling geomechanics and fluid flow. For example, the work by Zhang et al. simulates the dynamic changes in fracture aperture caused by pressure variations during production (i.e., the stress shadow effect) and its real-time impact on production distribution, profoundly revealing the intrinsic mechanism of how the "stress shadowing effect" evolves with production time, breaking through the limitations of static analysis [6]. Furthermore, Chen et al. proposed a new method integrating microseismic monitoring and production data inversion to evaluate the effective connected volume of the fracture network, offering a new perspective for quantifying "dead oil zones" and optimizing the timing for refracturing [7].

1.2.3 Coordinated control of energy supplement, water breakthrough risk, and microscopic displacement

For ultra-low permeability reservoirs with insufficient natural energy, how to effectively supplement energy through water injection while controlling water breakthrough risk is central to managing decline. Domestic and international research has progressed from demonstrating the necessity of water injection to optimizing injection methods and exploring microscopic displacement mechanisms.

Optimization of Water Injection Methods: Research by Jia et al. on the application of huff-and-puff water injection in tight oil reservoirs indicates that this cyclic injection-production method can more effectively promote imbibition and suppress water breakthrough risk by periodically altering the formation pressure field, serving as an important technical supplement to the traditional continuous water injection mode [8]. Sun et al. further explored the roles of asynchronous injection-production and pulse injection in balancing the displacement pressure field and improving sweep efficiency, providing new ideas for refined water injection management [9].

Microscopic Displacement Mechanisms: Capillary force-driven imbibition is recognized as a key mechanism. Pore-scale simulation research by Zhou et al. visually demonstrated the capillary-driven imbibition process under different reservoir wettability conditions, confirming the positive role of capillary forces at the microscopic scale while also providing a theoretical basis for understanding how it can transform into flow resistance (the Jamin effect) in later development stages [10]. Recent research (e.g., Xu et al.) has begun to focus on the competitive relationship between surface forces and capillary forces within nanopores and their

controlling effect on ultimate recovery, pushing mechanistic studies to an even more microscopic scale [11].

Early Warning and Intelligent: Prevention of Water Breakthrough: Water breakthrough is a key risk leading to a sharp deterioration in production decline. Current research hotspots focus on early warning and intelligent prevention of water breakthrough. Li et al. systematically analyzed water breakthrough patterns in horizontal wells under edge/bottom water conditions and summarized comprehensive water control strategies, including production profile adjustment and chemical water shut-off [12]. A review by Guo et al. systematically outlined the development from traditional profile control and water plugging to new materials such as nano-intelligent fluids and gel particles, emphasizing the importance of customizing prevention and control plans based on reservoir heterogeneity [13]. In recent years, real-time analysis of production performance data based on machine learning (e.g., Zhao et al.) is becoming a new tool for achieving early intelligent warning of water breakthrough [14].

Summary and Outlook :In summary, current domestic and international research on the decline of horizontal wells in ultra-low permeability reservoirs is evolving from simple matching of production history data to dynamic, integrated analysis deeply coupled with geological-engineering mechanisms. However, a major challenge and future direction in this field remains: how to holistically characterize core factors such as fracture network heterogeneity, multiphase flow mechanisms (especially the dynamic role transition of imbibition and capillary forces), and the long-range effects of injection-production interference within a unified simulation and prediction framework. It is precisely within this context that this study attempts to comprehensively utilize production data analysis, multi-fracture numerical simulation, and comparative analysis of typical well cases, aiming to systematically analyze the intrinsic logic and controlling factors of production decline in ultra-low permeability horizontal wells.

The technical approach of this paper is illustrated in Figure 1.

2. Research Area Overview and Data Foundation

2.1 Geological and Development Overview of the Wu Ping Block

The Wu Ping Block is located in the central part of the Northern Shaanxi Slope of the Ordos Basin. The main producing formation is the Chang 8 oil-bearing member of the Triassic Yanchang Formation. The reservoir has an average porosity of 10.5% and an average permeability of 0.3 mD, classifying it as a typical ultra-low permeability lithologic reservoir. The crude oil has an underground viscosity of 2.8 mPa·s, and the formation pressure coefficient ranges from 0.7 to 0.8, indicating insufficient natural energy. The block employs a diamond-shaped inverted nine-spot well pattern, primarily developed with multi-stage fractured horizontal wells, supplemented by water injection from surrounding vertical wells for energy maintenance.
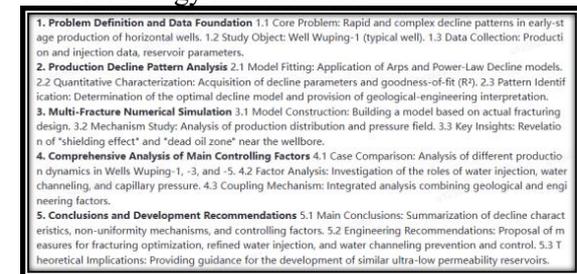

Figure 1. Technical Flowchart of This Paper

2.2 Research Subject and Data Sources

This study focuses on the analysis of production data from Wu Ping 1 Well (a horizontal well with a total depth of 2850 m, a horizontal section length of 800 m, and 10-stage fracturing) for approximately one year since its commencement in June 2012. For comparative analysis, adjacent wells Wu Ping 3 (exhibiting a good response to water injection) and Wu Ping 5 (experiencing water channeling) are selected as case studies. Data is sourced from the oilfield production database and includes daily/monthly oil production, liquid production, water cut, and injection data from water injectors. Basic reservoir properties and fracturing parameters are utilized for constructing the numerical simulation model.

3. Model Fitting and Analysis of Production Decline Laws

3.1 Decline Model Selection and Fitting Methodology

This study employs three classic models for

fitting: Exponential Decline (constant decline rate), Harmonic Decline (decline rate proportional to production), and Power-Law Decline (used to characterize early-stage fracture-dominated flow). The coefficient of determination (R^2) is used as the primary evaluation metric for the goodness of fit.

3.2 Fitting Results of Decline Laws for Wu Ping 1 Well

To quantitatively analyze the production decline pattern of Well Wu Ping 1 during the first nine months, we fitted the production data shown in Figure 2 using three classical decline models: harmonic, exponential, and power-law. The detailed fitting formulas, key parameters, and goodness-of-fit for each model are summarized in Table 1. The comparative analysis leads to the following key insights.

Harmonic Decline Fitting: The formula is q = 344.45 / (1 + 0.118t), with the highest R^2 value (>0.9685), indicating the best fit. This suggests that although the early decline rate of this well is

rapid, the decline rate itself gradually decreases over time, which aligns with the characteristic of slowly declining fracture conductivity after fracturing.
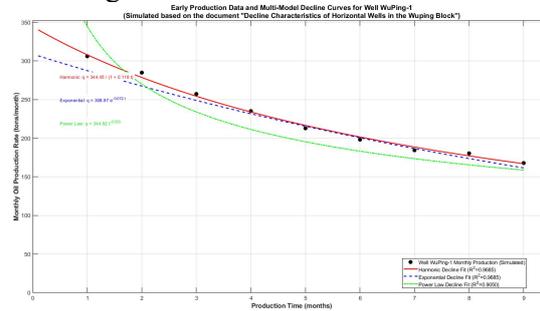

Figure 2. Early Production Data and Multi-Model Fitting Curves for Wu Ping 1 Well

Exponential and Power-Law Decline Fitting: Both models also achieved high fitting accuracy (R^2 values of 0.9685 and 0.905, respectively). The Power-Law decline formula, y = 344.92x$^{(-0.353)}$, reflects the flow regime characteristics associated with the fracture network in the early stage.

Table 1. Comparison of Fitting Parameters for Early Production Decline Models of Wu Ping 1 Well

Decline Model	Fitting Formula	Initial Fitted Production (tons/month)	Decline Coefficient (or Exponent)	Coefficient of Determination R^2
Harmonic Decline	q = 344.45/(1+0.118t)	344.45	0.118	0.9685
Exponential Decline	q = 308.97e^(0.072t)	308.97	0.072	0.9685
Power-Law Decline	q = 344.92t^(0.353)	-	0.353	0.905

3.3 Geological and Engineering Interpretation of Fitting Results

Mechanism of High Precision Fitting in the Early Stage: During the initial months of production, flow was dominated by fracturing fluid flowback and single-phase oil flow within the fractures. The fluid flow boundaries were relatively stable, meeting the physical premises of classic decline models.

Deviation and Model Failure in the Later Stage: After approximately six months of production, the pressure in the near-wellbore region dropped significantly. Crude oil degassing formed solution gas drive, changing the flow phase to oil and gas two-phase flow. This violated the Arps model's assumption of an "unchanged flow mechanism," causing subsequent data points to deviate from the fitted curves.

Significance of Decline Pattern Selection: The high fit of the Harmonic Decline model serves as a warning for the severity of the initial decline. However, it also implies that the decline trend will moderate in the future, providing a critical

time window for implementing mid-term production stabilization measures (such as water injection).

4. Research on Production Distribution Heterogeneity Based on Multi-Fracture Simulation

4.1 Establishment of the Numerical Simulation Model

Utilizing the reservoir property parameters (permeability, porosity, pressure) from the report and the fracturing design of the Wu Ping 1 Well (10 fractures, spacing approximately 80m), a two-dimensional multi-fracture numerical simulation model was established. The simulation aimed to characterize the production contribution of each fracture and the distribution of the pressure field after 40 days of production.

4.2 Analysis of Simulation Results: "Shielding Effect" between Fractures

The simulation results (see Figure 3) clearly reveal three fundamental patterns:
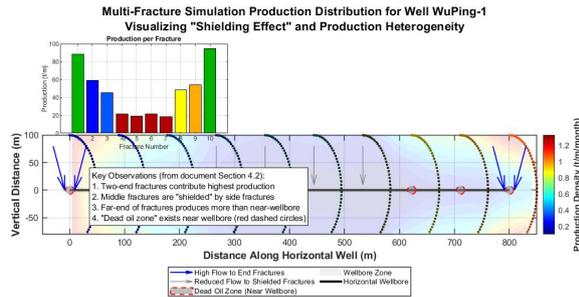
Figure 3. Multi-Fracture Simulation Production Distribution Map for Wu Ping 1 Well

High Production from Edge Fractures, Shielding Effect on Central Fractures: Fractures located at both ends of the horizontal well section contribute the most production because they control a larger drainage area and experience minimal interference from adjacent fractures. Central fractures are "shielded" by the edge fractures, resulting in limited pressure support range and significantly lower production.

High Production at Fracture Tips, Low Production Near the Wellbore: Within a single fracture, fluid primarily flows in from the fracture tip region (distal end). The fracture root area near the wellbore (proximal end) contributes less. This is because the pressure near the root drops more rapidly, making it prone to two-phase oil-gas flow or plugging.

"Dead Oil Zone" Near the Wellbore: A low-pressure, low-velocity stagnant zone forms near the root where the horizontal wellbore connects to the fractures. Crude oil in this zone is difficult to effectively mobilize, making it a potential area for remaining oil enrichment.

4.3 Engineering Implications: Optimization Directions for Fracturing Design

The existence of the "shielding effect" and "dead oil zone" directly leads to insufficient reservoir utilization and accelerated production decline. This suggests the following:

Optimize Fracture Spacing: It is necessary to find the optimal fracture spacing, through geomechanical stress field analysis and simulation studies, that avoids severe interference while maximizing reservoir coverage. Closer spacing is not always better.

Improve Fracture Uniformity: Efforts should be made to achieve balanced fracture propagation and conductivity across all fractures by optimizing fracturing processes (e.g., using diverting agents), thereby weakening the shielding effect.

Focus on Near-Wellbore Conductivity: Ensuring the conductivity of the fracture region near the wellbore is key to reducing the impact of the "dead oil zone" and improving overall fracture efficiency.

5. Comprehensive Control of Water Injection, Capillary Pressure, and Water Channeling on Decline Patterns

By comparing the production performance of different wells in the Wu Ping block, it can be seen that production decline is not an isolated phenomenon but is controlled by the coupling of multiple factors.

5.1 Case Comparison: Three Typical Decline Trajectories

In order to validate the potential of the multiphysics fully coupled model established in this paper for simulating complex flow and stress evolution, and to reveal the physical essence of productivity differences under various geological and engineering conditions, we conducted a comparative analysis of three typical production decline trajectories observed in the field (Figure 4). The differences in these trajectories essentially reflect the combined effects of reservoir geomechanical properties, fluid flow mechanisms, and artificial intervention outcomes, which are highly consistent with the mechanisms revealed by the model in this paper.

Wu Ping 1 Well Type (Poor Water Injection Response, Natural Decline): The early stage exhibits harmonic/power-law decline. In the later stage, due to insufficient energy replenishment, solution gas drive becomes dominant, and production drops to a low level. This reflects the poor production stabilization capability when relying solely on elastic drive and solution gas drive.
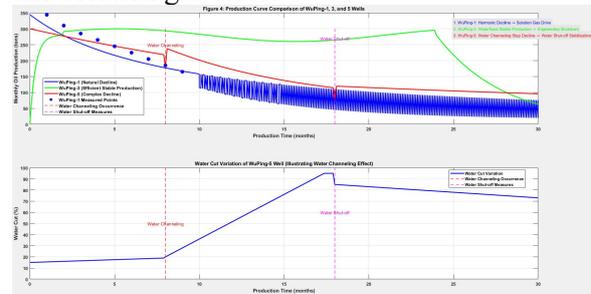

Figure 4. Comparison of Production Curves for Wu Ping 1, 3, and 5 Wells

Wu Ping 3 Well Type (Good Water Injection Response, Efficient Stable Production): Through

precise injection allocation from surrounding water injection wells, the formation energy is replenished in a timely manner. The production curve shows characteristics of long-term stable production. This indicates that effective water injection can fundamentally alter the decline trajectory, enabling long-term and efficient development.

Wu Ping 5 Well Type (Water Injection Induced Channeling, Complex Decline): Early water injection showed some displacement effect, slowing the decline. However, due to reservoir heterogeneity (presence of high-permeability streaks or large fractures), injected water "channels" along preferential pathways, leading to a rapid increase in water cut and a "step-like" decline in oil production. After implementing water shut-off measures, the declining trend was mitigated.

5.2 Mechanism Analysis of Core Controlling Factors

The "Double-Edged Sword" Effect of Capillary Pressure: In ultra-low permeability reservoirs, capillary pressure plays a significant role. In the early stage, capillary pressure acts as a driving force, promoting oil imbibition and replacement in the fracturing fluid filtrate zone, manifesting as power-law decline characteristics. As production proceeds and water cut rises, capillary pressure transforms into flow resistance (Jamin effect) in high water saturation zones, exacerbating production decline.

Streamline Distribution and Energy Utilization: The streamline distribution in a horizontal well multi-fracture system is complex. Effective water injection response implies the formation of effective injection-production streamlines, allowing for efficient utilization of elastic energy. Water channeling, however, indicates highly concentrated streamlines, leaving most areas untapped and resulting in extremely low energy utilization efficiency.

Dynamic Impact of Water Channeling: Water channeling not only causes high water cut and production reduction in the affected well but also, by channeling along high-permeability layers, alters the pressure field and the pseudo-radial distribution of streamlines around the horizontal well. This suppresses oil supply from other directions, fundamentally deteriorating development outcomes.

6. Conclusions and Development Recommendations

6.1 Main Conclusions

Horizontal wells in ultra-low permeability reservoirs of the Yanchang Oilfield experience severe early decline. The harmonic decline model often describes the characteristics of this stage with high accuracy, and its high decline coefficient reflects the essence of rapid post-fracturing productivity decay.

The production distribution among multiple fractures is extremely uneven. The "shielding effect" and the "dead oil zone" near the wellbore root are direct engineering causes for low reservoir utilization and rapid decline.

The long-term decline pattern of horizontal wells is controlled by the effectiveness of energy replenishment. Effective water injection can achieve stable production, while poor water injection response or induced water channeling leads to rapid production decline or catastrophic water breakthrough. Capillary pressure plays a dual role as both a driving force and a resistance at different development stages.

Production data analysis must be integrated with geological and engineering mechanisms. Solely relying on data fitting cannot predict turning points in decline patterns. It is crucial to identify key events such as the onset of solution gas drive or water channeling.

6.2 Recommendations for Ultra-Low Permeability Reservoir Development

Optimize Fracturing Design, Pursue Balanced Drainage: Conduct integrated geological and engineering studies to optimize fracture spacing, length, and conductivity profile. Utilize technologies like temporary plugging and diversion to mitigate the "shielding effect" and improve overall recovery efficiency.

Implement Precise Water Injection, Prevent and Control Water Channeling Risk:

Timing of Water Injection: Water injection should be initiated in a timely manner before the end of the dominant elastic energy period (i.e., before a significant inflection point appears in production) to replenish formation energy.

Method of Water Injection: Adopt a low-rate, gentle injection strategy to avoid fracturing pressure that could induce channeling. Strengthen the management of injected water quality to prevent internal fracture plugging.

Monitoring and Regulation: Utilize real-time production data and inter-well monitoring

technologies to dynamically identify signs of water channeling. Timely implement measures such as profile control, water shut-off, or adjusting injection-production relationships.

Deepen Mechanism Research, Develop Suitable Dynamic Analysis Tools: Considering the multiphase, non-linear flow characteristics of ultra-low permeability reservoirs, it is necessary to develop numerical simulation tools that integrate geomechanics, imbibition effects, and complex fracture networks. This will enable more accurate prediction of full lifecycle production performance and optimization of development strategies.

References

[1] Arps, J. J. Analysis of decline curves. Transactions of the AIME, 1945, 160(1): 228-247.

[2] Valkó, P. P. Assigning value to stimulation in the Barnett Shale: A simultaneous analysis of 7000 plus production histories and well completion records. In: SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, USA, 19–21 January 2009. SPE-119369-MS.

[3] Wang, H., Li, Y., Wang, S., Liu, X., Zhang, J. Production decline analysis of fractured horizontal wells in shale oil reservoirs considering stress-sensitive and multiphase flow. Energy Reports, 2023, 9: 345-356.

[4] Liu, X., Wang, D., & Zhang, G. A fractional decline curve analysis model for multi-fractured horizontal wells considering nonlinear flow mechanisms. Journal of Petroleum Science and Engineering, 2024, 235: 111234.

[5] Liu, P., Zhao, H., Li, M., Wang, J., Sun, Q. Quantitative evaluation of fracture interference and optimization of cluster spacing for multi-fractured horizontal wells in tight oil reservoirs. Petroleum Science, 2021, 18(5): 1371-1384.

[6] Zhang, F., Huang, T., Xu, R., Wang, C., Ma, L. Dynamic production performance and fracture interference of multi-fractured horizontal wells in low-permeability reservoirs: Insights from a coupled geomechanics and fluid flow model. Geoenergy Science and Engineering, 2023, 221: 211415.

[7] Chen, H., Li, M., & Wang, J. Evaluating effective fracture network volume and its impact on production decline in tight oil reservoirs using integrated microseismic and production data. SPE Journal, 2023, 28(3): 1456-1472

[8] Jia, C., Cheng, B., Wei, D., Li, X. Enhanced oil recovery in tight oil reservoirs via water injection huff-n-puff: Mechanism and application. Fuel, 2022, 310: 122289.

[9] Sun, B., Li, Y., & Zhang, S. Optimization of waterflooding strategies in ultra-low permeability reservoirs: A study on asynchronous and pulsed injection. Fuel, 2024, 357: 129876

[10] Zhou, W., Zhang, Y., Liu, H., Chen, X. Imbibition-driven oil recovery in fractured tight reservoirs: Pore-scale modeling and analysis. Water Resources Research, 2020, 56(8): e2020WR027190.

[11] Xu, R., Wang, C., & Liu, H. The competing effects of surface forces and capillary pressure on oil recovery in nanoporous tight reservoirs. Water Resources Research, 2023, 59(4): e2022WR033456

[12] Li, Y., Wang, C., Zhang, S., Liu, J. Early water breakthrough mechanism and water control strategies for horizontal wells in tight oil reservoirs with edge-bottom water. Journal of Petroleum Science and Engineering, 2021, 196: 107685.

[13] Guo, J., Wang, L., Yang, F., Zhou, H., Li, S. A comprehensive review of conformance control methods for water flooding in heterogeneous reservoirs. Petroleum Science, 2023, 20(1): 205-225.

[14] Zhao, L., Huang, F., & Wei, C. Early warning of water breakthrough in horizontal wells of tight oil reservoirs using machine learning and real-time production data. Journal of Petroleum Science and Engineering, 2024, 225: 111075.