Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2026, 14(9), 15-25
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Study on Seepage Law of Heavy Oil Reservoirs during Water Flooding Based on Ultra-Large-Scale Physical Simulation

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How to cite this paper: Xu, Y. N., Zhao, J. S., Sun, Q., Yuan, X., & Zhang, Y. C. (2026). Study on Seepage Law of Heavy Oil Reservoirs during Water Flooding Based on Ultra-Large-Scale Physical Simulation. *Journal of Geoscience and Environment Protection, 14,* 15-25.
https://doi.org/10.4236/gep.2026.149002

Received: August 3, 2026
Accepted: September 6, 2026
Published: September 9, 2026

Abstract

Aiming at the problems of developed dominant seepage channels and difficult mobilization of remaining oil in the late stage of ultra-high water cut in Bohai Q Oilfield, combined with the development characteristics of point bar lateral accretion bodies in meandering rivers, a large-scale physical model with a size of over 1+ m was established, and water flooding experiments were carried out under different well pattern modes. The results show that the ultra-large-scale model can effectively weaken the boundary effect and accurately characterize the gravity effect; the development mode has a significant impact on oil recovery; the evolution of the flow field presents the characteristics of vertical differentiation and planar heterogeneity; the synergistic effect of macroscopic physical property shielding at the interface and discontinuous microscopic capillary force leads to the enrichment of clustered remaining oil in the upstream of high-permeability zones. The research results provide an experimental basis and theoretical support for the well pattern optimization of lateral accretion bodies and the tapping of remaining oil potential in thick sandstone reservoirs in Bohai.

Keywords

Late Stage of Ultra-High Water Cut, Ultra-Large-Scale Physical Simulation, Lateral Accretion Body, Seepage Laws, Remaining Oil Distribution

1. Introduction

Bohai Q Oilfield is a large-scale integrated sandstone oilfield. After long-term water flooding development, it has entered the late ultra-high water cut stage with a comprehensive water cut of 96%, facing development contradictions such as rapid water cut rise, large production decline, low water injection efficiency and scattered remaining oil distribution (Zhu et al., 2020; Zhang & Liu, 2022). The reservoir of this oilfield is dominated by meandering river deposits, with widely developed lateral accretion bodies inside point bars, resulting in strong reservoir heterogeneity. The matching relationship between horizontal well pattern and lateral accretion architecture directly determines the water flooding sweep efficiency and spatial enrichment characteristics of remaining oil (Chen & Zhou, 2021; Wu et al., 2019).

At present, most physical simulation studies on reservoir seepage adopt two-dimensional cemented models or small-sized three-dimensional sand-packed models with a size ≤ 50 cm. Such models generally have limitations such as significant boundary effect, strong interference from built-in measuring points, and difficulty in accurately reproducing the macroscopic seepage characteristics of actual reservoirs (Dou et al., 2022). In recent years, reservoir physical simulation technology has gradually developed towards "large scale, high precision and multi-dimension". With the advantage of reproducing macroscopic reservoir heterogeneity, ultra-large-scale physical models can effectively reduce the interference of scale effect on experimental results and improve the accuracy of seepage law characterization (Wang et al., 2023; Li, 2021).

Domestic and foreign scholars have carried out a large number of physical simulation studies on seepage characteristics of conventional sandstone reservoirs. However, ultra-large-scale water flooding experiments focusing on the architecture of meandering river lateral accretion bodies are still relatively scarce. In particular, there are obvious deficiencies in the research on the coupling mechanism of well pattern mode, flow field evolution and remaining oil distribution (Zhang et al., 2020; Liu et al., 2022), and relevant experimental conclusions lack direct verification from field practice. In view of this, taking the meandering river point bar lateral accretion body of Bohai Q Oilfield as the geological prototype, this paper designs and fabricates a 1.3 m ultra-large-scale physical model based on the similarity principle, carries out water flooding experiments under different well pattern modes, systematically reveals the seepage law and remaining oil enrichment mechanism of lateral accretion reservoirs, and applies the research results to the development adjustment of the target oilfield, so as to provide experimental basis and technical support for the efficient development of similar oil reservoirs (Cheng et al., 2021).

2. Experimental Setup

2.1. Model Design Basis

Based on the high-precision seismic interpretation data, sealed coring analysis data and outcrop analogy data of Bohai Q Oilfield, an ultra-large-scale physical model with the size of 1.3 m × 1.3 m × 0.7 m was constructed in strict accordance with the similarity principle (Yang et al., 2020). The core similarity criteria are as follows:

1) Geometric similarity: The scale ratio between the geological prototype of the lateral accretion body and the physical model is set at 1:100. The outer dimension of the model is 1.3 m × 1.3 m × 0.7 m, and the effective size of the core lateral accretion simulation area is 1.0 m × 1.0 m × 0.4 m.

2) Physical property similarity: Referring to the measured permeability range of the target reservoir (300 - 5800 mD), the permeability interval of the model is set at 350 - 5500 mD to accurately reproduce the physical property differentiation characteristic of "high permeability in the inner part and low permeability in the outer part" of the lateral accretion body.

3) Fluid similarity: Simulated formation water with consistent salinity with formation water is prepared, and simulated oil with a viscosity of 162mPa·s, a density of 0.946g/cm^3, and an initial oil-water interfacial tension of 24mN/m is selected to ensure that the oil-water viscosity ratio is consistent with the prototype reservoir, so as to match the experimental mobility ratio with the field (Li et al., 2022).

4) Flow-rate similarity: Based on previous research findings, a single-well injection rate of 1.0mL/min is adopted.

2.2. Model Parameters and Fabrication

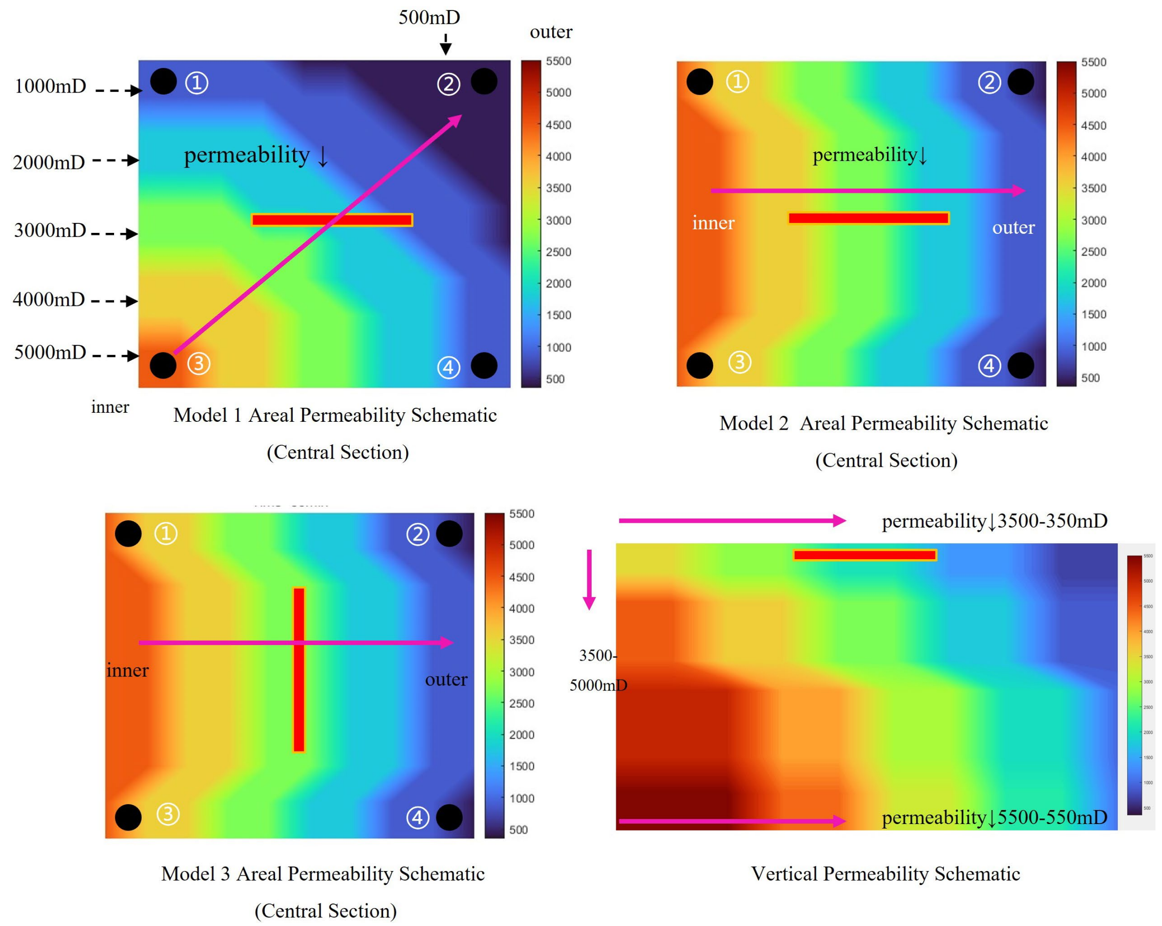

Figure 1. Schematic diagram of areal and vertical permeability distribution of lateral accretion bodies under different modes.

The size of the core reservoir simulation area of the model is 100 cm × 100 cm × 40 cm. The experiment is carried out under normal temperature and pressure. The constant injection rate of a single well is set at 1 mL/min, and the total injection pore volume multiple is 2 PV. Combined with the spatial matching relationship between well pattern and lateral accretion architecture, three development modes are designed: In Mode 1, Well ③ corresponds to the inner high-permeability zone, and Well ② corresponds to the outer low-permeability zone. For Modes 2 and 3, the line connecting Well ① and Well ③ covers the inner high-permeability zone, while the line connecting Well ② and Well ④ covers the outer low-permeability zone (Figure 1).

Monitoring planes are set at the buried depths of 10 cm (upper part), 20 cm (middle part) and 30 cm (lower part) in the vertical direction to monitor the seepage dynamics of different layers (Figure 2).

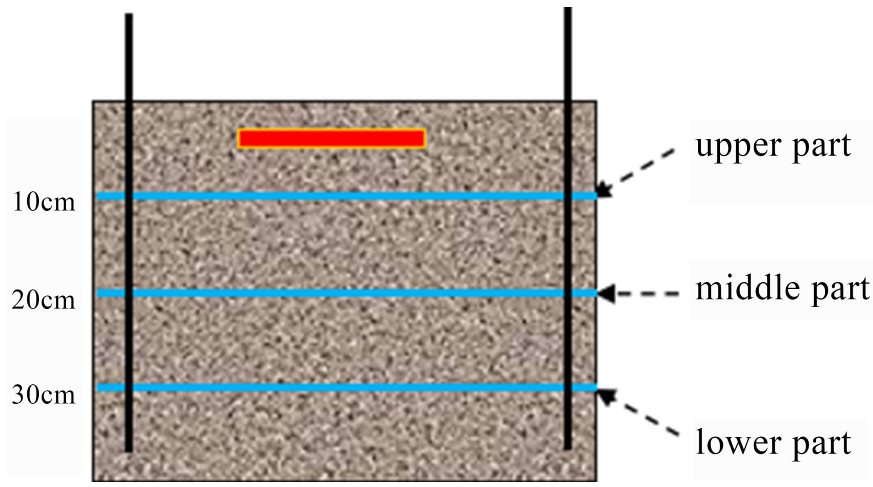

Figure 2. Schematic diagram of layered structure of lateral accretion body mode.

2.3. Experimental Procedure and Data Monitoring

The experimental process mainly includes three core links:

1) Vacuum pretreatment: The model is vacuumized to eliminate the interference of air in pores on the saturation process.

2) Fluid saturation: The multi-point alternating saturation method is adopted to saturate the formation water and simulated oil respectively at a constant pressure of 1 MPa. The global saturation test is carried out for every 10% pore volume saturation to ensure that the overall saturation error of the model is ≤2%.

3) Water flooding experiment: A four-point water flooding experiment is carried out at a constant flow rate of 1.0mL/min for each mode, with 4 injection wells injecting water synchronously and 1 horizontal well producing uniformly. During the experiment, the oil and water production and pressure change data at the production end are recorded for every 0.05 PV injection (Zhou et al., 2021).

A two-dimensional data acquisition system of "macro dynamic monitoring + microscopic imaging characterization" is adopted in the experiment. At the macroscopic level, the pressure dynamics and areal water saturation distribution characteristics of each monitoring point are collected in real time through high-precision pressure sensors and array resistivity monitoring system (Zhao et al., 2023). At the microscopic level, after the water flooding experiment, full-diameter core samples are drilled in the key areas with enriched remaining oil, and three-dimensional scanning imaging is performed using a Nanovoxel-5000CT scanner (resolution 0.5 μm) to reconstruct the occurrence morphology and distribution characteristics of remaining oil at the pore scale (Huang & Zhang, 2023).

3. Experimental Results and Analysis

3.1. Comparison of Oil Recovery under Different Development Modes

It can be seen from the oil recovery and water cut curves in **Figure 3**, when the water cut at the production end rises to 98%, the water flooding recovery factors under the three development modes are significantly different, with a maximum difference of 9.14%. Mode 1 has the best development effect, with a final recovery factor of 74.52%. Water breakthrough occurs the latest, and the water cut rises gently. Mode 2 has the worst development effect, with a final recovery factor of 65.38%. Water breakthrough occurs the earliest and the water cut rises the fasters. The recovery factor of Mode 3 is 69.00%, and the development effect is between the first two modes (Sun et al., 2024).

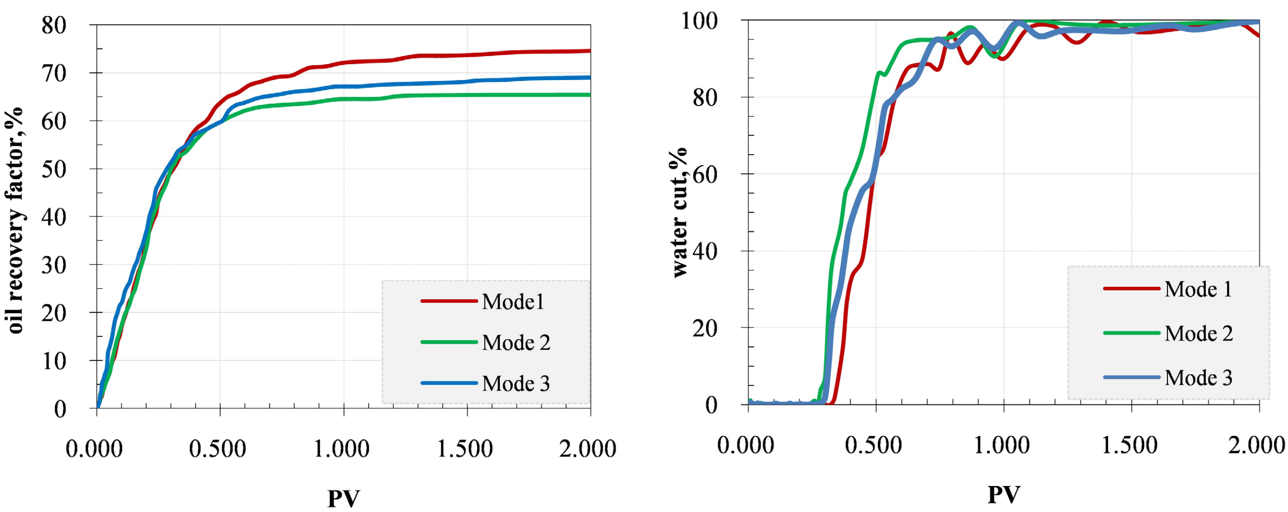

Figure 3. Curves of oil recovery and water cut variation for three development modes.

At the early stage of waterflooding development, injected water channels rapidly along high-permeability lateral accretion layers. As cumulative injection volume increases continuously, preferential flow channels gradually form between injection wells and horizontal wells along the high-permeability lateral accretion layers, and further evolve into extreme water-consuming zones with the continuous rise of water saturation. Upon entering the late ultra-high water-cut stage, nearly 30% of the reservoir area in the model has developed into extreme water-consuming zones. These zones consume approximately 90% of the injected water, leading to severe ineffective circulation of injected water and low overall waterflood oil displacement efficiency.

In Mode 1, under the combined effects of downward percolation of injected water in high-permeability zones and planar displacement in low-permeability zones, injected water establishes displacement connectivity preferentially at the reservoir bottom, and vertical remaining oil is mainly enriched in the upper reservoir intervals between wells in low-permeability zones. In Mode 2, the planar displacement front advances rapidly at the high-permeability end, while remaining oil between injection wells and horizontal wells in low-permeability zones is characterized by low producing degree and high proportion of remaining reserves. In Mode 3, although the well pattern orientation is optimized to match the architecture of lateral accretion bodies, constrained by the combined influences of reservoir heterogeneity and fluid bypassing effect, partial low-permeability intervals still cannot be effectively swept by waterflooding, resulting in significant remaining oil enrichment in the middle-upper reservoir.

3.2. Flow Field Evolution and Saturation Distribution Patterns

3.2.1. Areal Flow Field Characteristics

Based on the areal oil saturation distribution under different injection multiples (**Figure 4**), it can be seen that the injected water in Mode 1 presents a displacement characteristic of "converging from the periphery to the center": the high-permeability zone has the two-way seepage advantage of "vertical infiltration and areal diffusion", while the low-permeability zone is dominated by areal displacement.

Vertically, the high-permeability lateral accretion layer at the bottom of the model has the most uniform sweep degree. In the low-permeability zone, the areas on both sides of the line between injection wells and horizontal wells are the main enrichment zones of remaining oil. In the middle layer, water channeling channels are preferentially formed in the high-permeability zone, and the displacement front advances significantly faster than that in the low-permeability zone. After water breakthrough in the horizontal well in the upper layer, the remaining oil gradually shrinks from the initial annular distribution and finally presents C-shaped and dotted scattered enrichment.

Affected by the symmetry of the well pattern, the areal flow fields of Mode 2 and Mode 3 present mirror distribution characteristics. However, there are always unswept stagnant zones between injection wells in the low-permeability zone under both modes, and the remaining oil saturation maintains at 35% - 45%, which is the key area for subsequent potential tapping.

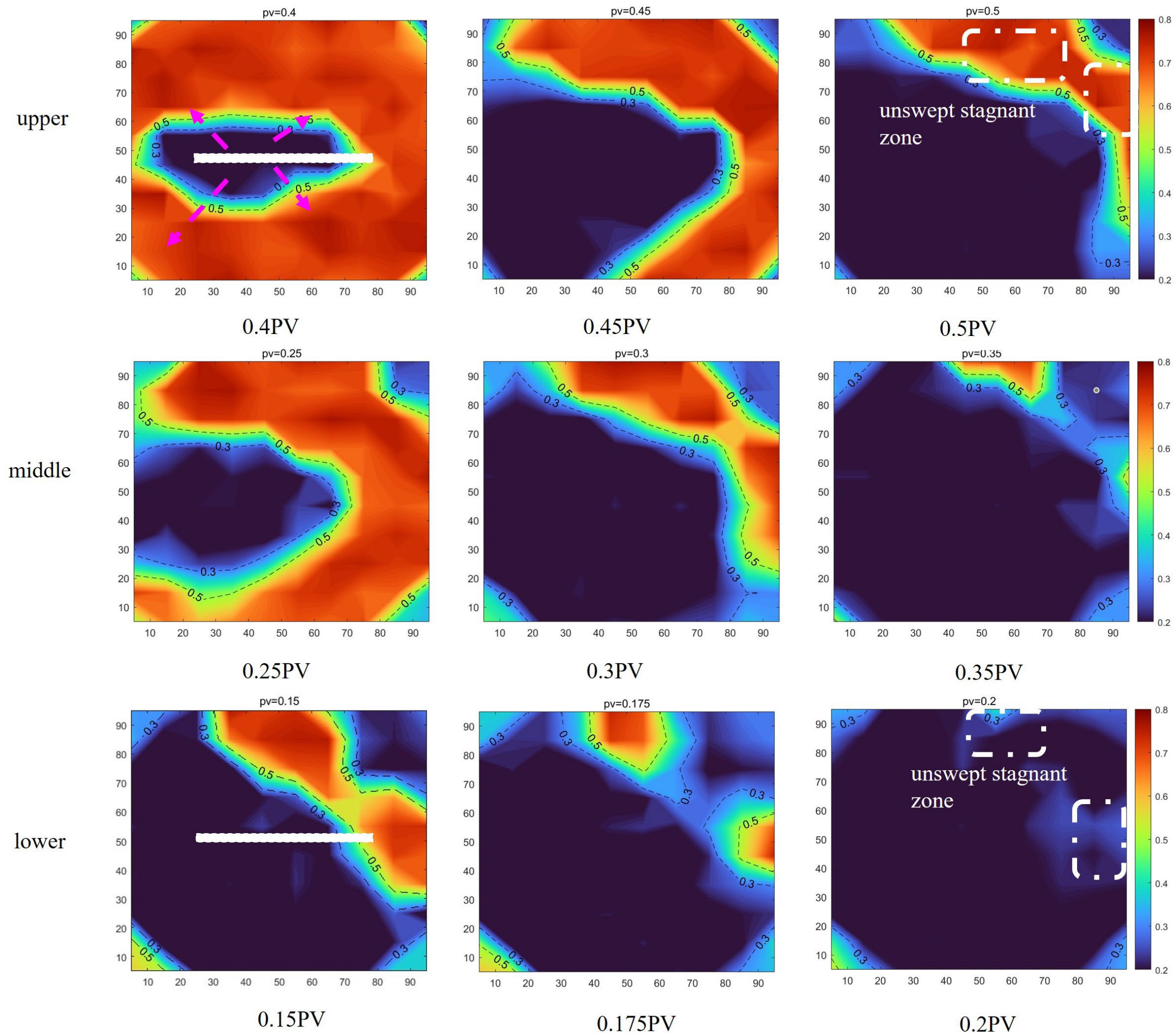

Figure 4. Planar oil saturation distribution of Mode 1 under different injection multiples.

3.2.2. Vertical Seepage Characteristics

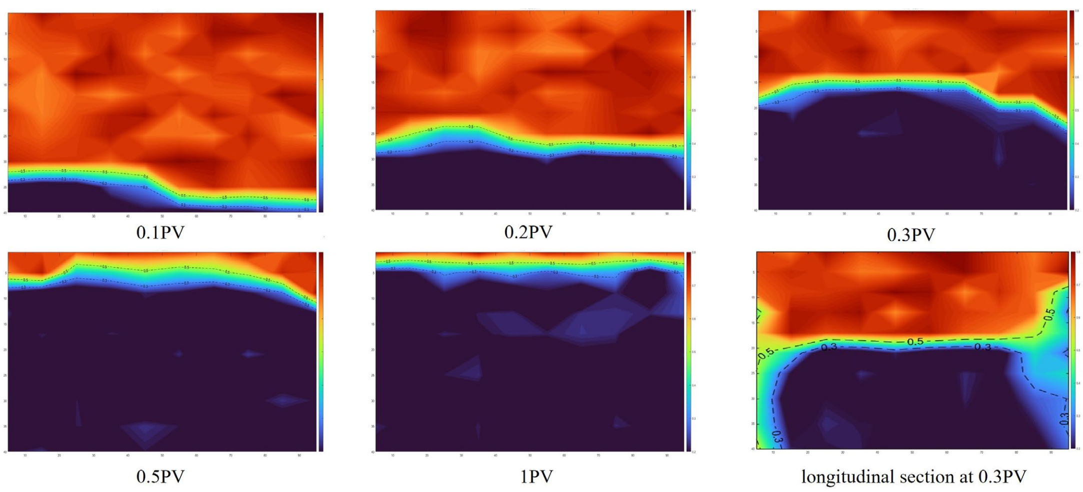

Figure 5. Vertical oil saturation distribution under different injection multiples in Mode 1.

Vertically, under the joint control of lateral accretion reservoir heterogeneity and positive rhythm sedimentary characteristics, the oil saturation in the model presents an overall distribution law of "high in the upper part and low in the lower part", and the vertical differentiation effect of injected water is very significant.

Under the coupling effect of vertical infiltration of injected water in high-permeability zones and areal displacement in low-permeability zones, injected water preferentially migrates downward along the vertical seepage channels of high-permeability zones. Under the action of gravity differentiation, the water phase gradually occupies the lower space of the reservoir, and crude oil is displaced upward, finally forming a "overlap-type" displacement characteristic from bottom to top (Figure 5).

3.3. Enrichment Mechanism of Remaining Oil at Interfaces

Through CT scanning imaging and core sample analysis, it is found that under the dual control of macroscopic physical property shielding and microscopic capillary force discontinuity, the remaining oil at the interface between high and low permeability lateral accretion bodies presents an asymmetric distribution characteristic of "enrichment in the upstream and water flooding in the downstream" (Figure 6, Figure 7).

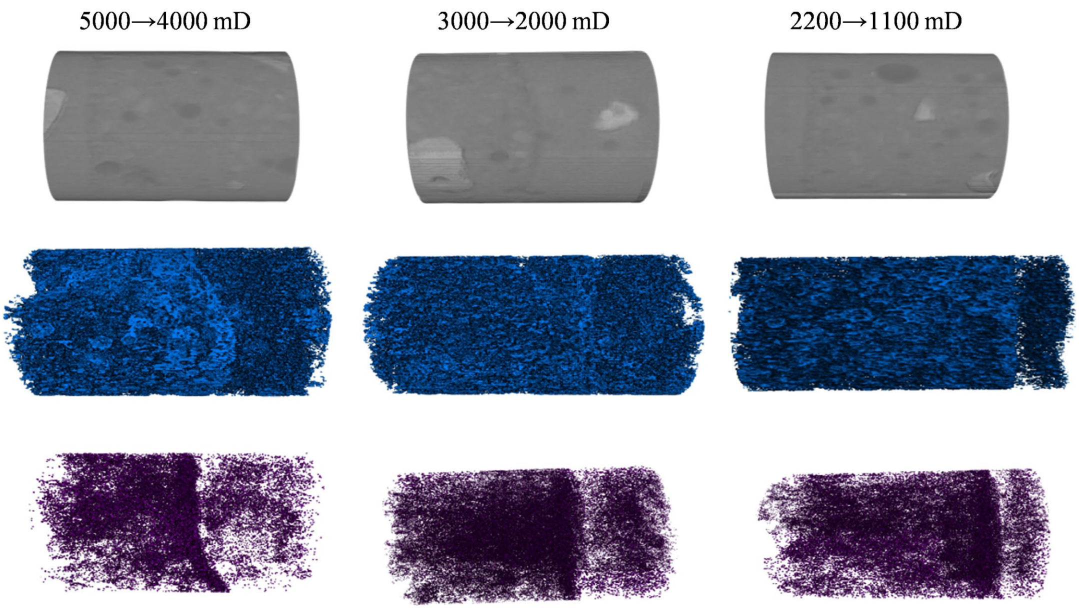

Figure 6. Analysis of CT scanning results.

According to the capillary equilibrium theory, oil and water phases need to meet the pressure continuity condition on both sides of the interface. However, the difference in pore-throat structure between coarse-grained sandstone (high-permeability zone) and fine-grained sandstone (low-permeability zone) leads to significantly different capillary forces ($Sw1 \neq Sw2$), which eventually results in discontinuous water saturation on both sides of the interface (Yang et al., 2020).

During water flooding, the water phase advances faster in the high-permeability zone. After the water front reaches the lateral accretion interface, it is sucked into the low-permeability zone under the action of capillary force. The high irreducible water saturation in the low-permeability zone will block the continuous migration path of crude oil and divide the crude oil into dispersed remaining oil. After the water phase breaks through the interface and advances rapidly along the high-permeability zone, a large amount of massive "passing oil" will remain upstream of the interface in the high-permeability zone, which is wrapped by the continuous water phase and forms difficult-to-produce retained remaining oil (Li et al., 2022; Wang et al., 2022).

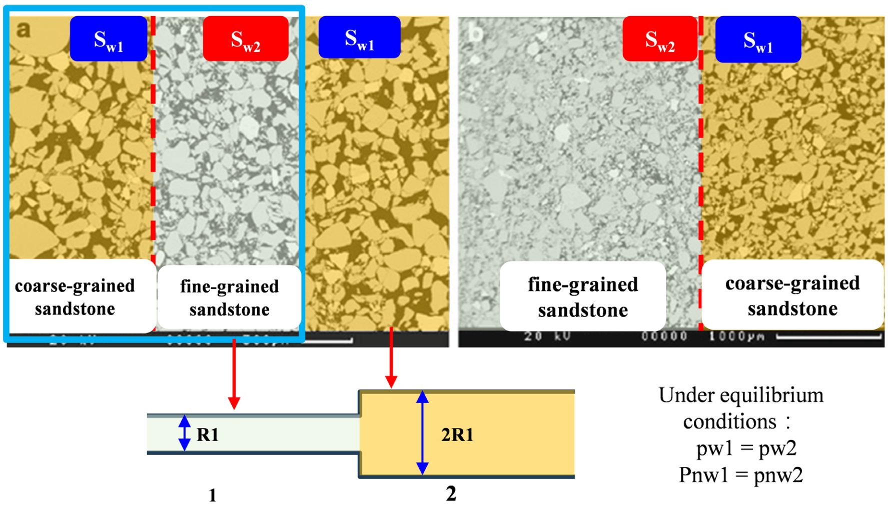

Figure 7. Spatial distribution of water saturation in the reservoir on both sides of the interface.

4. Field Application

Based on the seepage law and remaining oil enrichment mechanism revealed by the experimental results, field trials were carried out in a typical meandering river point bar block of Bohai Q Oilfield with differentiated flow field regulation measures. For high-permeability zones, integral profile control and flooding operations were implemented in 4 well groups to plug dominant seepage channels; for low-permeability zones, cyclic water injection tests were conducted in 8 well groups to tap the potential of dispersed remaining oil.

The implementation achieved remarkable oil-increasing effects: the peak daily oil increment of the well groups reached 105 m^3/d, the comprehensive water cut dropped by 0.5%, and the annual oil increment hit 15,000 m^3. This technology boasts good popularization and application value.

5. Conclusion and Recommendations

Based on the geological prototype of lateral accretion reservoirs in Bohai Q Oilfield, this paper conducts water flooding experiments with an ultra-large-scale physical model. Combined with field application practices, the following conclusions are drawn.

1) The ultra-large-scale physical model with a size of over 1 m can effectively weaken measuring point interference and boundary effect, accurately characterize the seepage features of lateral accretion bodies in thick sandstone reservoirs, and truly reproduce the controlling effects of gravity differentiation and reservoir heterogeneity on the seepage process.

2) The development mode has a significant impact on water flooding performance. Mode 1 adopting "fixed-point injection in the inner high-permeability zone" delivers the optimal development effect, with the latest water breakthrough, the gentlest water cut rise and the highest recovery factor. Mode 2 with the well pattern intersecting the high-permeability zone performs the worst.

3) The evolution of water flooding flow field in lateral accretion reservoirs generally presents the characteristics of vertical differentiation and areal heterogeneity. High-permeability zones are dominated by vertical "on lap-type" displacement, while low-permeability zones are dominated by areal displacement. The dominant flow field develops progressively along high-permeability lateral accretion layers and eventually forms high water-consumption zones. Remaining oil is mainly enriched in the upper inter-well intervals of low-permeability zones and the interface areas of lateral accretion bodies.

4) The enrichment of remaining oil at lateral accretion interfaces is jointly controlled by macroscopic physical property shielding and microscopic capillary force discontinuity, and the millimeter-scale micro-structures at the interfaces further aggravate the remaining oil locking effect. Massive remaining oil upstream of the interface in high-permeability zones and dispersed remaining oil in low-permeability zones are the main targets for potential tapping.

5) Field application indicates that the comprehensive regulation technology of "architecture-matched well pattern + profile control in high-permeability zones + pulsed water injection in low-permeability zones" developed from experimental results can effectively improve development performance and has certain popularization and application value.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Chen, F., & Zhao, W. (2021). Application of Ultra-Large-Scale Physical Simulation Technology in Reservoir Seepage Research. *Oilfield Chemistry, 38,* 320-325. (In Chinese)

Cheng, L. S., Wang, P., & Liu, Y. T. (2021). Physical Simulation Experiment on Water Flooding Law of Point Bar Lateral Accretion Bodies in Meandering Rivers. *Journal of Xi'an Shiyou University (Natural Science Edition), 36,* 43-50. (In Chinese)

Dou, H. E., Jia, A. L., & He, D. B. (2022). *Development Theory and Practice of Reservoirs at Ultra-High Water Cut Stage*. Petroleum Industry Press. (In Chinese)

Huang, S. J., Li, J., & Zhang, F. X. (2023). Influence of Lateral Accretion Heterogeneity on

Water Flooding Effect and Regulation Countermeasures. In *Proceedings of 2023 National Reservoir Engineering Academic Conference* (pp. 189-196). China University of Petroleum Press. (In Chinese)

Li, A. F. (2021). *Microscopic Seepage Characteristics and Remaining Oil Occurrence Mechanism of Meandering River Point Bar Reservoirs*. Master's Thesis, China University of Petroleum (East China). (In Chinese)

Li, S. K., Wang, J., & Lü, X. H. (2022). Lateral Accretion Body Identification and Remaining Oil Tapping Technology in Bohai Meandering River Reservoirs. *China Offshore Oil and Gas, 34,* 128-136. (In Chinese)

Liu, H., Yang, L. P., & Zhou, F. J. (2022). Field Test of Flow Field Regulation Technology for Bohai Oilfield at Ultra-High Water Cut Stage. In *Proceedings of 2022 National Oilfield Chemistry Technology Symposium* (pp. 45-51). Petroleum Industry Press. (In Chinese)

Sun, H. Q., Wang, Z. L., & Yang, Y. F. (2024). New Progress in Development Technology of Bohai Oilfield at Ultra-High Water Cut Stage. *Petroleum Exploration and Development, 51,* 438-448. (In Chinese)

Wang, J., Li, M. Y., & Lin, M. Q. (2022). Capillary Force Mechanism at Lateral Accretion Interface and Production Law of Remaining Oil. *Oilfield Chemistry, 39,* 721-727. (In Chinese)

Wang, N. T., Liu, G., & Yang, X. T. (2023). Optimization of Remaining Oil Tapping Technology for Bohai Sandstone Reservoirs at Ultra-High Water Cut Stage. *China Offshore Oil and Gas, 35,* 134-142. (In Chinese)

Wu, Y. X., Li, Z., & Wang, L. H. (2019). Scale Effect of Reservoir Physical Simulation and Construction Technology of Ultra-Large-Scale Model. *Acta Petrolei Sinica, 40,* 956-965. (In Chinese)

Yang, Z. J., Zhu, W. Y., & Song, K. P. (2020). Research Progress of Enhanced Oil Recovery Technology by Chemical Flooding in Ultra-High Water Cut Reservoirs. *Oilfield Chemistry, 37,* 556-563. (In Chinese)

Zhang, L. H., Sun, L., & Li, Y. (2020). Coupling Method and Application of Pore Network Model and Macroscopic Numerical Simulation. *Journal of Southwest Petroleum University (Science & Technology Edition), 42,* 1-12. (In Chinese)

Zhang, W., & Liu, F. (2022). Distribution Law of Remaining Oil in Point Bar Lateral Accretion Bodies of Meandering Rivers. *Petroleum Exploration and Development, 49,* 580-590. (In Chinese)

Zhao, X. L., Wu, X. D., & Li, Z. F. (2023). Error Analysis and Correction of Water Flooding Experiment with Ultra-Large-Scale Physical Model. *Journal of Xi'an Shiyou University (Natural Science Edition), 38,* 51-58. (In Chinese)

Zhou, J. L., Yang, J., & Zhang, Y. (2021). Identification and Regulation of Dominant Seepage Channels in Reservoirs at Ultra-High Water Cut Stage. *Oil Drilling & Production Technology, 43,* 825-832. (In Chinese)

Zhu, X. M., Chen, H. Q., & Zhang, Q. (2020). Architecture of Point Bar Lateral Accretion Bodies and Remaining Oil Distribution in Meandering Rivers: A Case Study of Qinhuangdao 32-6 Oilfield in Bohai Sea. *Petroleum Exploration and Development, 47,* 521-532. (In Chinese)