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# Application of Cyclic Water Injection in Bohai Heavy Oil Reservoirs

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## Abstract

Oilfield Q is a typical heavy oil reservoir, characterized by high porosity, high permeability, high crude oil viscosity, active edge and bottom water, and loose reservoirs that are prone to sand production. Since it was put into production in 2001, good development results have been achieved through comprehensive management measures such as optimized water flooding, infill well adjustment, separate-layer series development, and well pattern modification. It has now entered the late stage of development, showing characteristics such as rapid water cut rise, significant production decline, and low water flooding efficiency. Through the study of mechanism models, this paper screens out suitable blocks and optimizes the cyclic water injection parameters, achieving good results. It can provide a theoretical basis and reference for improving the development effect of heavy oil reservoirs in the ultra-high water cut stage.

## Keywords

Heavy Oil Reservoir, Late-Stage Development, Cyclic Water Flooding, Application

## 1. Introduction

As an important component of petroleum resources, heavy oil accounts for a considerable proportion of global oil reserves. Heavy oil resources in China are widely distributed, and with the continuous advancement of development, many heavy oil reservoirs have entered the ultra-high water cut stage (water cut greater than 80%). At this stage, conventional water flooding development faces a series of problems, such as low water injection efficiency, accelerated decline in oil well production, and complex distribution of remaining oil. These issues lead to increased development costs and decreased economic benefits. Therefore, it is of great practical significance to explore effective development adjustment technologies to improve the recovery efficiency of heavy oil reservoirs in the ultra-high water cut stage.

Cyclic water flooding is a technology that adjusts the flow state of fluids in the reservoir and improves the reservoir development effect by periodically changing the water injection rate or water injection pressure. This technology has achieved good application results in some conventional reservoirs and low-permeability reservoirs (Yin, 2001), but there are still certain controversies and uncertainties regarding its application in heavy oil reservoirs at the ultra-high water cut stage (Graham & Richardson, 1959; Qiao, 2019; Zhang, 2017; Lyu & Zhang, 2007). This paper aims to explore the feasibility of cyclic water flooding in heavy oil reservoirs at the ultra-high water cut stage, providing a theoretical basis and reference for the practical application of this technology.

## 2. Mechanism of Action of Cyclic Water Injection

Cyclic water flooding is a water injection development method that relies on the existing well pattern and regularly changes the working system of oil and water wells. Taking well groups as units, it alternately changes their injection modes to establish an unstable pressure drop in the oil reservoir. This promotes the development of reservoir zones, layers, and sections that were previously not swept by water, thereby improving the sweep efficiency of heterogeneous reservoirs and enhancing crude oil recovery (Mu et al., 2006).

### 2.1. Elastic Effect Caused by Pressure Disturbance

The pressure perturbation of pulsed cyclic water flooding creates an oil-water cross-flow process between high-permeability and low-permeability zones (Yang et al., 2009). During the pressure-increasing cycle, when the pressure in the high-permeability zone is higher than that in the low-permeability zone, the pressure perturbation drives water and even a portion of oil to flow into the low-permeability zone. In the pressure-decreasing cycle, when the pressure in the high-permeability zone is lower than that in the low-permeability zone, the pressure perturbation forces the oil in the low-permeability zone to flow into the high-permeability zone (Huang et al., 1995). From an overall perspective, a certain amount of water is always trapped in the low-permeability zone, so a certain amount of oil always flows into the high-permeability zone (Yu & Zhang, 1993; Yu & Zhang, 1994).

During the pressure-increasing cycle, since the oil in the high-permeability zone is displaced first and part of it enters the low-permeability zone, the oil saturation in the high-permeability zone decreases while that in the low-permeability zone increases. In the pressure-decreasing cycle, the oil in the low-permeability zone is displaced by the high pressure in the low-permeability zone and enters the high-permeability zone; at this time, the oil saturation in the high-permeability zone increases, while that in the low-permeability zone decreases. This process is repeated, which can not only improve oil displacement efficiency but also enhance sweep efficiency in heterogeneous formations, thereby optimizing water flooding performance and increasing water flooding recovery.

### 2.2. Changing the Direction of Injection-Production Flow Lines

After long-term water flooding development with a linear opposite horizontal well pattern, most water injection wells and oil production wells form flow lines perpendicular to the horizontal section of horizontal wells, oriented directly opposite each other. The single direction of injection-production flow lines leads to high water cut in oil production wells and low reservoir recovery degree.

To address the above issues, the original linear horizontal well pattern was modified to a periodic alternating water injection well pattern by adjusting the water injection strategy. Through this adjustment, the direction of some original flow lines was changed. This changes the direction of injection-production flow lines, ensuring that the untapped areas at the heel or toe of horizontal wells in the original injection-production well pattern are well swept (Yin & Xue, 2009; Gong, 2010).

### 2.3. Improve the Swept Volume of Water Flooding

Under the effect of interlayer pressure difference, a large amount of water in the high-permeability layer flows into the low-permeability layer and displaces the oil into the high-permeability water-flooded layer until pressure balance is achieved. During the pressure reduction stage, the high-permeability water-flooded layer has a large pressure transmission coefficient, leading to a rapid pressure drop. As a result, the high-permeability layer first becomes a low-pressure layer, while the low-permeability layer, in contrast, turns into a high-pressure layer (Chen, 2003; Yin, 2001). In this way, under the combined action of interlayer pressure difference and capillary pressure gradient, the oil in the low-permeability layer is displaced into the high-permeability layer and then driven away by water until pressure balance is reached again. The two processes above cycle continuously, ultimately enabling the oil in the low-permeability layer to continuously enter the high-permeability layer and be displaced by water.

## 3. Development Characteristics of Oilfield Q

### 3.1. Geological Reservoir Characteristics

Oilfield Q is a large-scale complex fluvial heavy oil field in the Bohai Bay Basin, characterized by a large-scale low-amplitude anticline structure. It has an average porosity of 32% and an average permeability of 2300 mD, with the underground crude oil viscosity ranging from 22 to 260 mPa·s. The main oil-bearing formations are the lower member of the Neogene Minghuazhen Formation and the upper member of the Guantao Formation. This oilfield exhibits characteristics such as relatively high crude oil viscosity, active edge and bottom water, and loose reservoir structure prone to sand production.

### 3.2. Development History and Current Status

Oilfield Q was put into production in 2001. In the early stage, multiple sets of pay zones were produced together using directional wells, which led to rapid water cut rise and significant production decline. Stable production at a relatively low level was maintained through water plugging, optimized water flooding, and liquid production enhancement measures. From 2013 to 2015, comprehensive adjustments focusing on horizontal well development by separate reservoir series and flow field regulation were implemented: first, vertically, the reservoir was divided into separate series, with the original single development series adjusted to three, enabling separate production of oil layers with different reservoir types and fluid properties; second, horizontally, the well pattern was modified, changing the early directional well inverted nine-spot well pattern to an irregular combined five-spot well pattern with horizontal wells for oil production and directional wells for water injection.

After long-term development of the oilfield, water flooding is generally present at the bottom of the main sand bodies, while water flooding in the middle and upper parts is relatively mild, with remaining oil concentrated in the middle and upper parts. As of the end of October 2023, the oilfield has a total of 396 wells, including 254 oil production wells and 142 water injection wells. The oilfield has a daily oil production capacity of 5439 tons, a cumulative crude oil production of 42.9701 million tons, a recovery degree of developed reserves of 26.0%, an oil production rate of developed reserves of 1.2%, and a comprehensive water cut of 96.8%, entering the late stage of ultra-high water cut.

### 3.3. Current Existing Problems

The main sand bodies of the oilfield have entered a development stage characterized by high recovery degree and ultra-high water cut. After long-term development, the dynamic heterogeneity has further intensified, with intra-layer and planar contradictions becoming increasingly prominent. High water-consuming zones are relatively well-developed, and the problem of ineffective water circulation is conspicuous, resulting in high water cut and low recovery degree. Meanwhile, affected by reservoir heterogeneity, there are significant differences in development effects across different planar regions: severe water flooding occurs in some well areas, while a large amount of remaining oil in other well areas remains untapped. The existing injection-production adjustment technologies cannot meet the demand for precise matching between the displacement field and the remaining oil saturation field in the ultra-high water cut stage, so it is necessary to further explore a water injection method suitable for the oilfield's current development stage.

## 4. Feasibility Study on Cyclic Water Injection

### 4.1. Mechanism Model Study

By referring to the geological and reservoir characteristics of Oilfield Q, a mechanism model for interlayer heterogeneous high-permeability reservoirs was established. The model has a planar grid step of 10 meters and a vertical grid step of 1 meter, with a water body connected to the bottom of the lower layer. The planar well pattern adopts a five-spot configuration, and the production wells are horizontal wells with a well spacing of 350 meters. The model parameters are shown in Table 1, and the permeability diagram of the reservoir mechanism model is presented in Figure 1. The scheme research is conducted using Petrel RE software. For the cyclic water injection method, the daily injection rate of injection wells is 400 $m^3/d$, while the production wells operate with a fixed daily fluid production rate of 800 $m^3/d$. The injection wells follow an alternating pattern of injecting for 1 month and shutting down for one month.

Table 1. Parameters related to the mechanism model.

| Thickness m | Permeability Range mD | Average Permeability mD | Average Porosity |
|---|---|---|---|
| 15 | 500 - 3500 | 2000 | 0.3 |

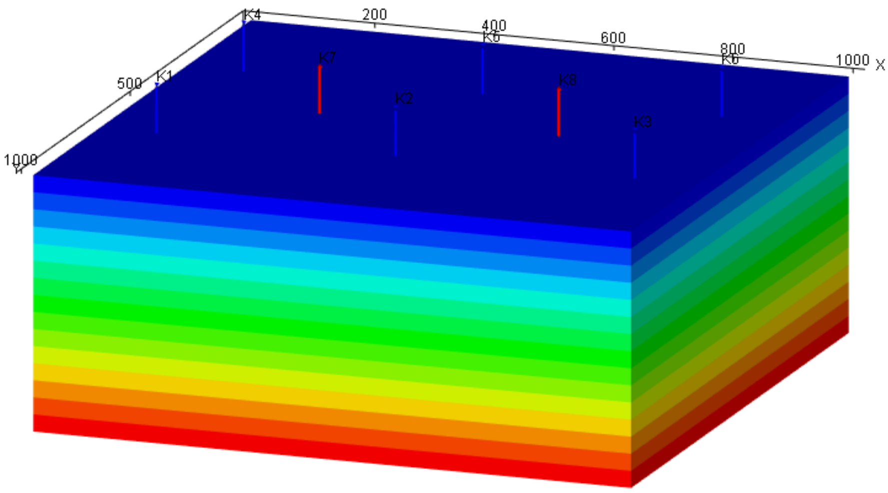


Figure 1. Permeability diagram of the mechanism model.

Based on the mechanism model, factors influencing the effect of cyclic water injection are analyzed from aspects such as crude oil viscosity, reservoir heterogeneity, and water volume multiple. The following conclusions are obtained through reservoir numerical simulation research:

① The higher the crude oil viscosity, the worse the effect of cyclic water injection. As crude oil viscosity increases, the channeling resistance and imbibition resistance between high-permeability and low-permeability layers rise, leading to a decrease in cumulative oil production. Consequently, the additional oil production from cyclic water injection compared to conventional water injection is reduced.

② The stronger the reservoir heterogeneity, the worse the effect of cyclic water injection. The differences in water saturation and oil saturation between high-permeability and low-permeability layers are significant, leading to a severe phenomenon of injected water fingering along high-permeability layers. As a result, the additional oil production of cyclic water injection compared with conventional water injection decreases.

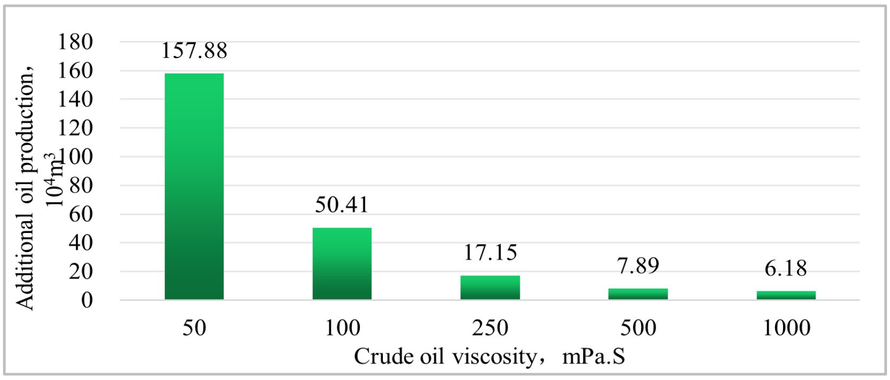


**Figure 2.** Additional oil production curves of cyclic water injection for different viscosity.

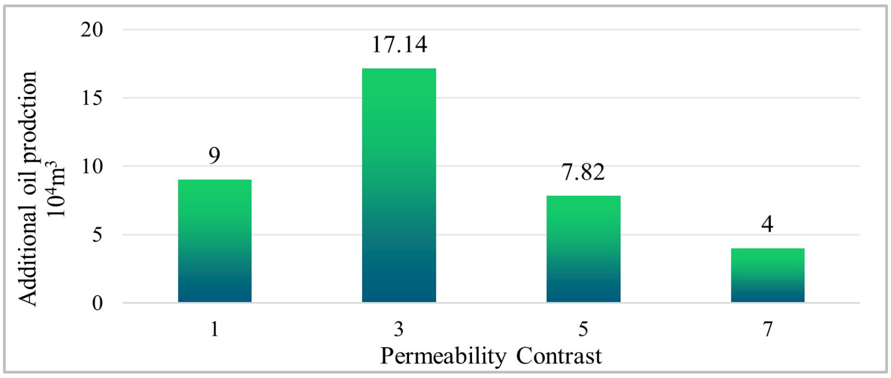


**Figure 3.** Additional oil production curves of cyclic water injection for different heterogeneity level.

③ The larger the water volume multiple, the worse the effect of cyclic water injection. Affected by the bottom water, the reservoir has a short water-free oil production period, early water breakthrough in oil wells, and rapid water cut rise, resulting in a reduction in the additional oil production of cyclic water injection, compared with conventional water injection. For thinner sand bodies, cyclic water injection makes it easier to achieve effective reservoir production, and the oil recovery factor is higher than that of conventional water injection.

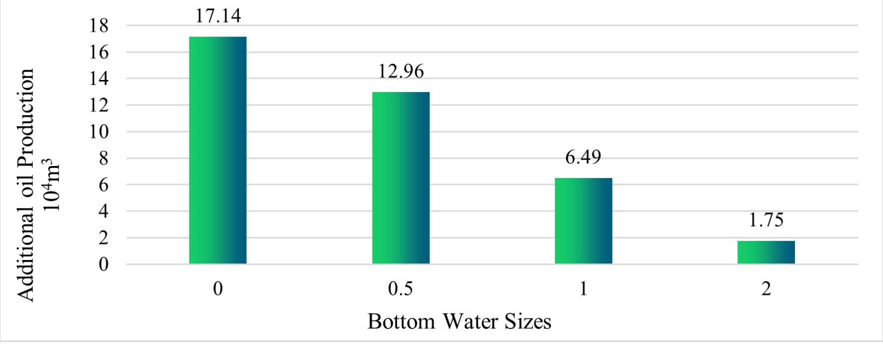


**Figure 4.** Additional oil production curves of cyclic water injection for different bottom water sizes.

In conclusion, the factors influencing the oil displacement effect of cyclic water injection, in descending order of significance, are: crude oil viscosity > reservoir heterogeneity > water volume multiple.

Based on the influencing factors of the oil displacement effect of cyclic water injection and a comprehensive analysis of the development status of the well pattern flow field, the conditions for cyclic water injection to be applicable in Oilfield Q shall meet the following three criteria:

① Low crude oil viscosity, low mobility ratio (less than 1.5), strong vertical reservoir heterogeneity (with a permeability contrast of less than 5), and either no bottom water or only secondary bottom water;

② Located in weakly developed and potentially developed areas, featuring a well-completed well pattern, good injection-production correspondence, verified by tracer tests or production performance response, and a relatively large number of responsive wells;

③ Significant differences in the distribution of remaining oil between layers.

### 4.2. Parameter Optimization

According to the applicable conditions (see Figures 2-4), 5 sand bodies were selected for the cyclic water injection test, and the parameters were optimized. Taking the P2-P4 well group in the NmIII2 sand body of the North Block as an example (Figure 5), this well group has a large number of weakly developed and potentially developed areas, with relatively concentrated remaining oil distribution, a well-completed well pattern and good injection-production correspondence, making it suitable for carrying out cyclic water injection work. Parameter optimization was conducted from aspects such as cyclic water injection mode, alternating cycle and water injection intensity. The results show that the intermittent water injection and alternating water injection modes have better effects; the shorter the cycle, the higher the cumulative oil production and the better the stable water flooding effect; when the water injection allocation per well is 1 to 1.5 times the original water injection volume, the oil displacement effect is better (see Figures 6-8).

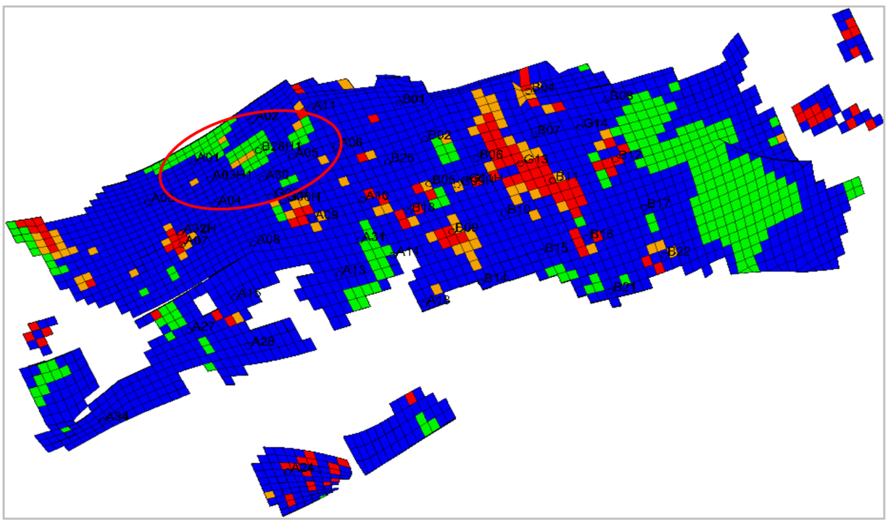

Figure 5. Flow field development of NmIII2 sand body in the north block of oilfield Q.

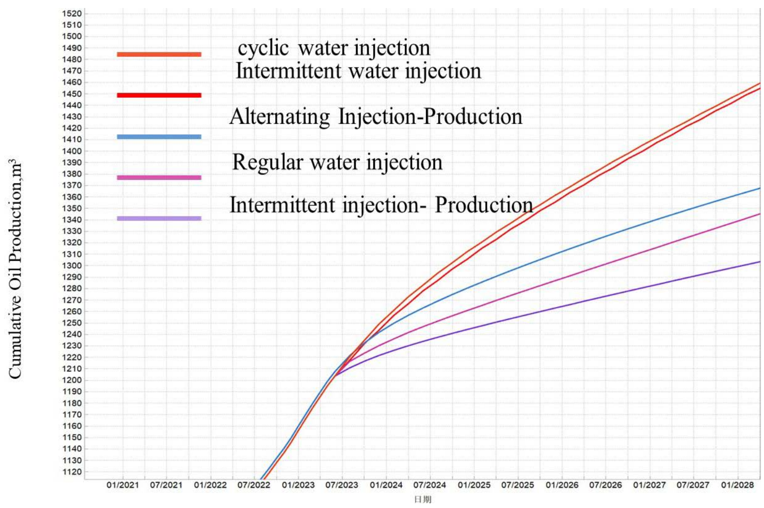


**Figure 6.** Cumulative oil production under different cyclic water injection modes.

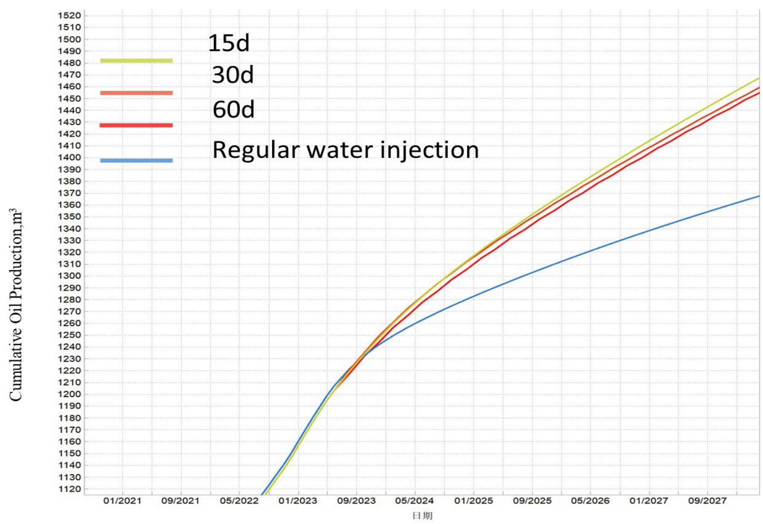


**Figure 7.** Cumulative oil production under different alternating cycles.

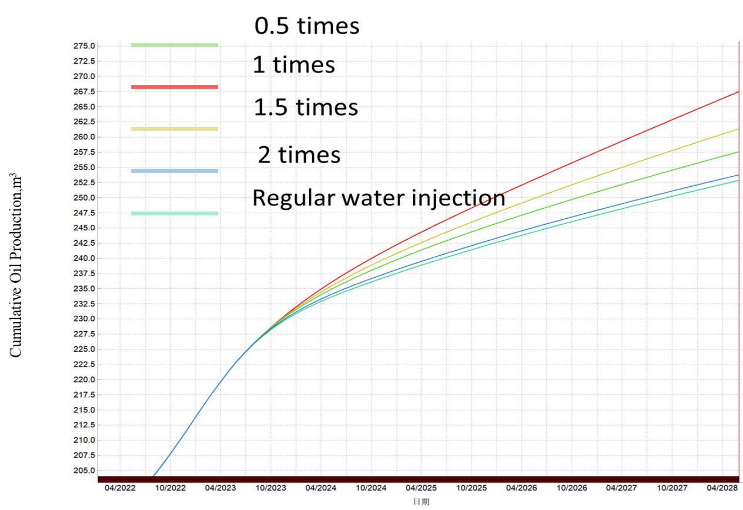


**Figure 8.** Cumulative oil production under different water injection intensities.

### 4.3. Application Effect

Q oilfield has carried out cyclic water injection tests since 2022, transitioning from a one-way water flooding injection-production well pattern to a row-type injection-production well pattern, and gradually expanding to a five-spot injection-production well pattern. Based on the findings of reservoir numerical simulation studies, the alternating water injection method is adopted, with a water injection cycle of half a month and an allocated injection volume per well of 1 times the original. By the end of 2024, 70 well groups have been implemented, among which 36 well groups are effective, 15 well groups are pending observation, and 19 well groups are ineffective. In the past year, the water cut rise rate has accelerated, the adaptability of cyclic water injection has weakened, and its effect has gradually deteriorated.

With the progression of water injection development, the proportion of preferential channels increases gradually. Pure cyclic water injection is insufficient to improve the areal sweep efficiency. Since 2024, attempts have been made to combine cyclic water injection with large-slug profile control and displacement. Four water injection well groups have been deployed. These well groups attained a peak daily oil increment of 92 $m^3$/d, and to date, their daily oil increment is maintained at 43 $m^3$/d. The cumulative net oil increment of the well groups has surpassed 15,000 $m^3$, and they continue to be within their effective period. Through large-slug profile control and displacement to block preferential channels, cyclic water injection expands the areal sweep, resulting in a significant improvement in oil increment effect. The areas with strong flow field development have decreased, and the blocking of preferential channels has been effective.

## 5. Results and Discussion

1) Oilfield Q is a typical heavy oil reservoir, characterized by strong reservoir heterogeneity, complex fluid properties, ultra-high water cut stage, and poor development performance. The development effect of conventional water injection is relatively poor, thus requiring the adoption of effective development adjustment technologies.

2) Cyclic water injection exhibits a certain degree of feasibility in the ultra-high water cut stage of heavy oil reservoirs through action mechanisms such as pressure field adjustment, seepage field improvement, and redistribution of remaining oil.

3) By establishing a mechanism model, factors influencing the effect of cyclic water injection were analyzed from aspects such as crude oil viscosity, reservoir heterogeneity, and water volume multiple, and blocks suitable for cyclic water injection were screened out.

4) Typical well groups were selected to conduct pilot tests, and parameter optimization was carried out from aspects such as cyclic water injection mode, alternating cycle, and water injection intensity. Favorable results were achieved, and the application scope was gradually expanded. According to the geological reser-

voir characteristics of different regions, suitable water injection methods were adopted to improve the water flooding development effect.

## Conflicts of Interest

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

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