



Study on evaluation and reconstruction of reservoir seepage field in high water cut stage based on analysis of seepage characteristics

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Abstract

Aiming at the problem of a reservoir in the high water cut stage, and specifically an understanding of the distribution of the residual oil, the existing evaluation methods cannot effectively reflect the flow and distribution of the underground fluid. In this contribution, the seepage field is divided into six sections based on the evaluation of the seepage characteristics of the high water content in the reservoir. The seepage field evolution processes were studied respectively from the different well patterns and the reservoir heterogeneity, and a corresponding seepage field reconstruction method is proposed based on the flow field equilibrium. The results show that the seepage field partition can well reflect the characteristics of the different development stages of reservoir seepage. The seepage field evaluation and reconstruction method is applied to the Nm3-4-1 layer of Gang Dong oilfield, where the water content decreased by 3.8%, and the variation coefficient of the seepage field decreased by 0.33. The evaluation method is of great significance for the exploitation of the remaining oil in high water cut reservoirs.

Keywords Seepage field · High water cut period · Seepage field evaluation · Flow field reconstruction · Flow field strength

Introduction

Reservoir seepage field is a new research direction which has arisen in recent years. Due to the differences between geological data, development methods and research methods, the division method of seepage field is also not completely consistent (Brigham 1983). Hearn et al. (1984) found that the different physical properties of different parts of the reservoir have different control effects on the production dynamics, thus the concept of the flow unit was proposed. According to the main characteristic the dominant seepage field is strong. Wang et al. (2010) used a cluster analysis method to determine whether there are large channels in each oil well according to the different dynamic data characteristics of oil and water wells. Xin et al. (2012) introduced the flow intensity index as a quantitative index, and

combined it with the pore volume number index, recovery level and water injection efficiency to quantify the formation and the stage of the advantage channel quantitatively. Jiang et al. (2012) selected the pore radius and water ratio, water content and fluid flow rate as evaluation indexes, and established the reservoir seepage field evaluation system using analytic hierarchy process and a fuzzy comprehensive evaluation method. According to the principle of flow reorganization, pattern adjustment, layer adjustment and production system adjustment are used to improve recovery (Zhang et al. 2014; Feng et al. 2015). However, the widely used seepage field evaluation method can only be used to determine flow intensity using a comprehensive index and cannot reflect the characteristics of the seepage flow field in the evolution of the historical present stages of a reservoir.

With the development of oilfield, exploration of the remaining oil at the high water cut stage has become a hot topic. In the high water-bearing period, due to the high heterogeneity, it is easy to form a predominant channel under long-term water flood, which is unfavorable to the production of the site (Sun et al. 2004). The development of the superiority channel of the Guan Tao group is 34.7% in the Gu Dao oil field, as determined by an interwell tracer test of 39 Wells (Cui and Zhao 2004). Many scholars have studied

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the laws relating to physical changes in the reservoir during the high water cut stage. Flesenthal and Gangle (1975) defined a thief zone as a relatively thin layer comprising 5% or less of the net pay thickness and taking more than 25% of the injected water in a given well. Dou et al. (2001) combined the reservoir engineering method with the gray theory method to study whether large pore path was formed or not and the direction of its extension. Feng et al. (2013) showed that dimensionless pressure index can identify thief zones easily and verified its validity from both the synthetic model and the pilot test. Davies and Dongen (2013) presents interwell communication as a means to detect the location of thief zones in a controlled acid jetting well using distributed temperature sensing technology along with a production logging tool and water flow log for the first time. However, these researches focused to determine whether the large pore paths are formed or not at a specific time point. Few studies have been able to quantify the dominant flow channel through numerical simulation and determine the partition of the dominant flow channel through the seepage field zoning.

Based on the characteristics of reservoir seepage, we established an evaluation standard for the reservoir historical index and current status index, dividing the seepage field into six types. The corresponding method of reconstructing the seepage field is put forward to guide remaining oil development and improve the recovery ratio.

Study on evaluation method of reservoir seepage field in high water cut period

The evaluation of a reservoir seepage field should not only reflect the characteristics of water flooding percolation in various stages but also take into account the evaluations of the history and present situation (Musial et al. 2012). The main idea of this study is to consider the historical reservoir evaluation index, determine the ineffective water circulation area, the non-producing reserves area, high flow and low flow strength area; considering the present reservoir evaluation index to determine the critical flow velocity. Thereby, the high speed percolation area and low speed percolation area are defined. Finally, a new evaluation system for the seepage field is formed.

Evaluation of ineffective water circulation area

Based on the water flooding experiment of nine coring wells in the Gang Dong oilfield, the fitting of experimental results from high power water drive showed that with increasing water saturation, the semi-logarithmic relationship curve defined by $\frac{K_{ro}}{K_{rw}}-S_w$ showed a downward bending characteristic when entering the late stage of high water cut

development. Statistics of the Gang Dong oilfield well Lq11 in water displacing oil experimental data showed that even under high water drive, the oil displacement efficiency increased significantly, but at this time, the relative permeability of the water phase increased significantly (Allen 1983; Jordan and Pryor 1992). The ratio of oil–water relative permeability in the semi-logarithmic coordinate system was transformed from a linear to a nonlinear form (Fig. 1).

Based on the above experimental results, when the ratio of oil to water relative permeability begins to form an inflection point, the corresponding water saturation is the sign of an invalid water cycle area. A five-point numerical simulation model is set up using the Dagang oilfield reservoir property parameters, and the invalid water cycle area is described. Under the $\frac{K_{ro}}{K_{rw}}-S_w$ semi-logarithmic coordinate system, taking the position of the inflection point corresponding to a water saturation of 0.75 as the standard for the division of the invalid water cycle area, according to Fig. 2, the invalid water cycle area is first formed near the water well.

Comparing the polymer-surfactant dual-compound flooding and water flooding after the invalid water circulation area accrued (Table 1), it is obvious that after the SP flooding, the recovery of the oil reservoir is improved and the water consumption reduced. Thus, we can take the appearance of the ineffective water circulation area as a symbol of the need to change the development scheme.

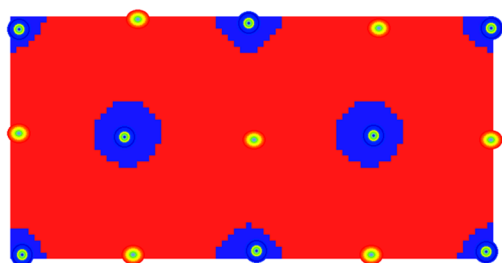
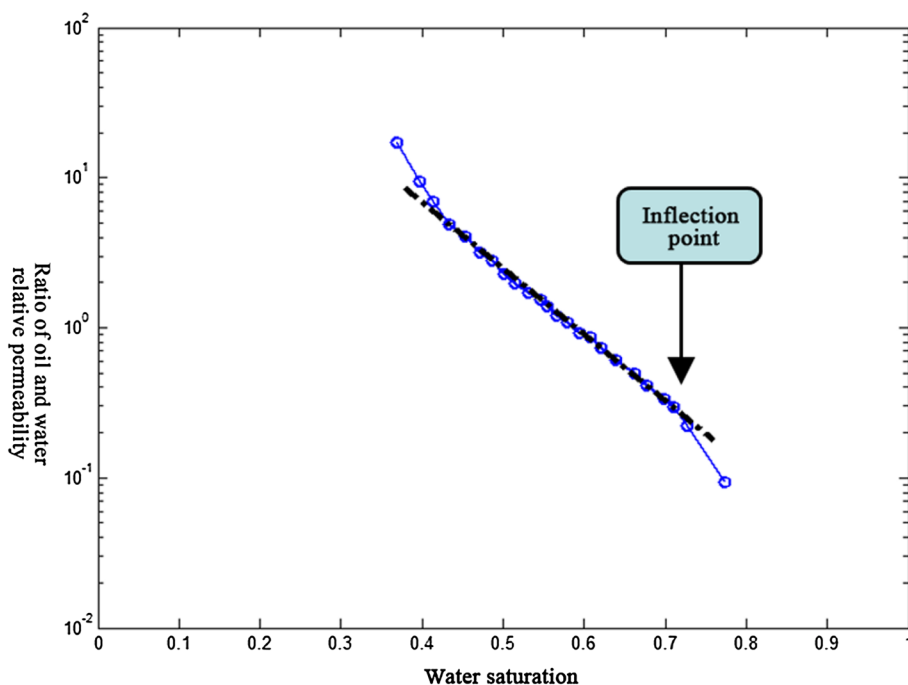
Evaluation of fluid intensity

The classification of fluid strength is mainly based on the analytic hierarchy process to identify the most influential parameters in the development stage of the reservoir, determining the logical relationship among different factors and finally forming the parametric indicators that characterize fluid strength. The reservoir parameter is the intrinsic expression of dynamic parameters. For an oil reservoir in the high water cut stage, the well pattern is relatively perfect, and the fluid strength is mainly affected by the water flow rate. Therefore, the cumulative water volume in each direction of the reservoir will be used as a dynamic indicator for evaluating the fluid strength. The equation is:

$$M = \sum_0^T \left(\frac{Q_x}{D_x D_z} + \frac{Q_y}{D_x D_z} + \frac{Q_z}{D_x D_y} \right) \Delta t. \quad (1)$$

In the formula, M is the cumulative water flow through a cross-section of the reservoir, m^3 ; Q_x is the fluid which flows across the X -direction during Δt time, m^3 ; Q_y is the fluid which flows across the Y -direction during Δt time, m^3 ; Q_z is the fluid which flows across the Z -direction during Δt time, m^3 ; D_x is the length of the X -direction cross-section, m ; D_y is the length

Fig. 1 Relation curve of water saturation and ratio of oil and water relative permeability



■ Effective water circulation area ■ Invalid water circulation area

Fig. 2 The distribution map of the invalid water circulation area and the effective water circulation area

of the *Y*-direction cross-section, *m*; *D_z* is the length of the *Z*-direction cross-section, *m*; Δt is the unit time interval, *s*.

Due to the large difference in the accumulation of water flow in each region at the late stage of water drive development, we use a logarithmic function to normalize the result via the expression:

$$L = \frac{\ln M(i) - \ln M(i)_1}{\ln M(i)_2 - \ln M(i)_1} \tag{2}$$

In the formula, *L* is the fluid strength coefficient; *M*(*i*)₁ is the minimum value of cumulative water flow; *M*(*i*)₂ is the maximum value of cumulative water flow.

The proportion of movable parts in the remaining oil of a reservoir is represented by the movable oil coefficient, with the expression:

$$R = \frac{S_O - S_{or}}{S_{oi} - S_{or}} \tag{3}$$

In the formula, *R* is the movable oil coefficient; *S*_O is the current oil saturation; *S*_{or} is the residual oil saturation; *S*_{oi} is the original oil saturation.

According to the normalized results, we combined the fluid strength parameters and the movable oil coefficient, and partitioned the evaluation results. Among the results, a movable oil coefficient in the range 0–0.3 represents a low potential area, a movable oil coefficient in the range 0.3–0.8 represents a high potential area and a movable oil coefficient in the range 0.8–1 represents non-producing area, see Table 2.

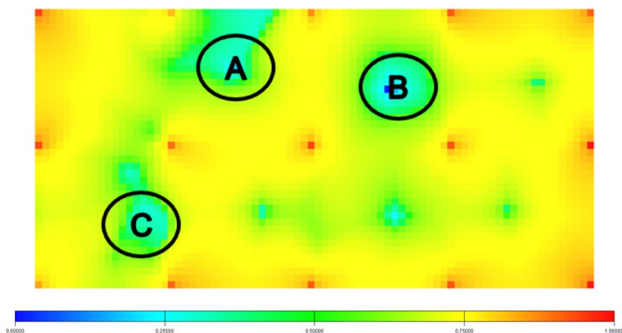
Taking a five-point well pattern of a heterogeneous reservoir as an example, the distribution of fluid strength in the

Table 1 Comparison of development effect of continuous water flooding and SP flooding after the formation of ineffective water circulation area

Development scheme	Water consumption (m ³)	Recovery percent (%)	Water content (%)
Continuous water flooding after the emergence of invalid water circulation area	35,756	33.8	98.5
SP flooding after the emergence of invalid water circulation area	9453	37.6	96.9

Table 2 Evaluation of fluid intensity areas

Movable oil coefficient	Fluid strength coefficient	Partition
0–0.3	0.6–1	Low potential area
0.3–0.8	0.1–0.6	High potential area
0.8–1	0–0.1	Non-producing area

**Fig. 3** Distribution of fluid intensity in high water cut period

high water cut stage is evaluated. The reservoir thickness is 5 m, the reservoir porosity is 0.2 and the permeability ratio is 10. Under the influence of reservoir heterogeneity, the fluid intensity presents a differential distribution. Physical properties in the region marked A are poor, and the position is in the interwell stagnation area, an accrued non-producing area in the high water cut stage. The fluid flow in the regions marked B and C is affected by the physical properties of the reservoir, the displacement intensity is weak and this forms a high potential area. Other regions had good physical properties, large accumulative overflow and these form low potential areas (Fig. 3). Therefore, it can be seen that the fluid intensity partition can reflect the static parameters of the reservoir and the influence of the historical development on the development effect.

Evaluation of percolation velocity

From Sects. “Evaluation of ineffective water circulation area” and “Evaluation of fluid intensity” parts, we can see that the invalid water circulation area and the fluid intensity partition are both evaluating the seepage field during the historical development of the reservoir, and cannot represent the characteristics of the seepage field at the current time (Felsenthal and Gangle 1975; Luchi et al. 2012; Leckie and Smith 1992). Thus, we introduce the evaluation of the critical seepage velocity. According to the formula for oil–water two-phase flow:

$$V_t = \frac{q_w + q_o}{Bh} = \left(\frac{K \times K_{rw}}{\mu_w} + \frac{K \times K_{ro}}{\mu_o} \right) \frac{dp}{dx} \quad (4)$$

In the formula, V_t is the seepage velocity of oil–water two-phase flow, m/d; q_w is the aqueous phase flow, m³/d; q_o is the oil phase flow, m³/d; B is the well space, m; h is the thickness of oil layer, m; K is the absolute permeability of oil reservoir, 10⁻³ μm²; K_{rw} is the relative permeability of water phase, 10⁻³ μm²; K_{ro} is the relative permeability of oil phase, 10⁻³ μm²; μ_w is the aqueous phase viscosity, mPa s; μ_o is the oil phase viscosity, mPa s; Wang et al. (2014) studied the formula for the economic production of single well in high water cut and it can be obtained as follows:

$$q_1 = \frac{C_G \times 10^4 / 365}{(1 - f_w)(P - R) - C_v} \quad (5)$$

In the formula, q_1 is single-well economic liquid output, m³/d, C_G is annual fixed cost of single well, Million Yuan; P is crude oil price, Yuan/ton, R is tonnage dues of oil, Yuan/ton, C_v is variable costs of ton liquid, Yuan/ton.

The seepage velocity corresponding to the economic limit production volume under the control area of a single well is considered as the critical seepage velocity. When the present regional seepage velocity is larger than the critical seepage velocity, this means that the current area has a higher driving capacity; otherwise, the current driving capacity is insufficient. The expression for the critical seepage velocity is as follows:

$$V_{th} = \frac{q_1}{B \times h} \quad (6)$$

In the formula, V_{th} is the critical percolation velocity, m/d.

Taking the physic parameters of the Gang Dong oil reservoir as an example to establish a line well pattern streamline model, the single well fixed cost is 800 thousand Yuan, the price of crude oil is 1960 Yuan/ton, the variable cost of oil is 790 Yuan/ton, and oil tax is 250 Yuan/ton. The reservoir is divided into a high speed percolation area and a low speed percolation area based on the critical seepage velocity (Fig. 4).

The division of the seepage velocity area solves the disadvantage relating to the fact that the streamline field can only describe the flow state at the present time qualitatively, and the results show that the high velocity seepage area is mainly distributed in the mainstream channel between the oil and water wells, whilst the low velocity seepage area is distributed between the water wells or the oil wells.

Based on the above seepage field evaluation method, the seepage field is divided into six types, namely the non-producing reserves area, the low speed and high potential area, the high speed and high potential area, the low speed

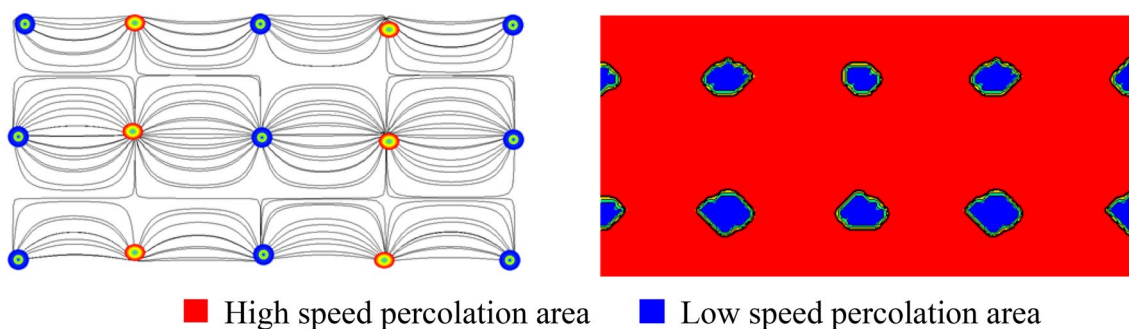


Fig. 4 Schematic diagram of streamline and seepage velocity zone of line well pattern

and low potential area, the high speed and low potential area and the invalid water circulation area. The potential of the residual oil in different regions is not the same, with the remaining potential of the non-producing reserves area being the largest, while the residual potential of the invalid water circulation area is the smallest.

Study on the evolution law of seepage field

We design a line well pattern and a five-point well pattern to evaluate the flow field evolution law when the water content was 40, 80, 90, 95%. The variation of the flow field in each

stage is shown in Figs. 5 and 6. For a line well pattern at the early stage of development, there is a large amount of non-producing reserves area between the oil wells, low velocity and high potential area exists between the water wells and some parts of the high velocity and high potential area exists between the oil and water wells. When the water content reaches 80%, low speed and high potential area only exists between the oil wells or the water wells and high speed and low potential area is formed between the oil and water wells. With the increase of water content, the low velocity and high potential area gradually decreases. When the water content reaches 95%, low velocity and high potential areas are scattered between the oil wells or water wells, and low velocity

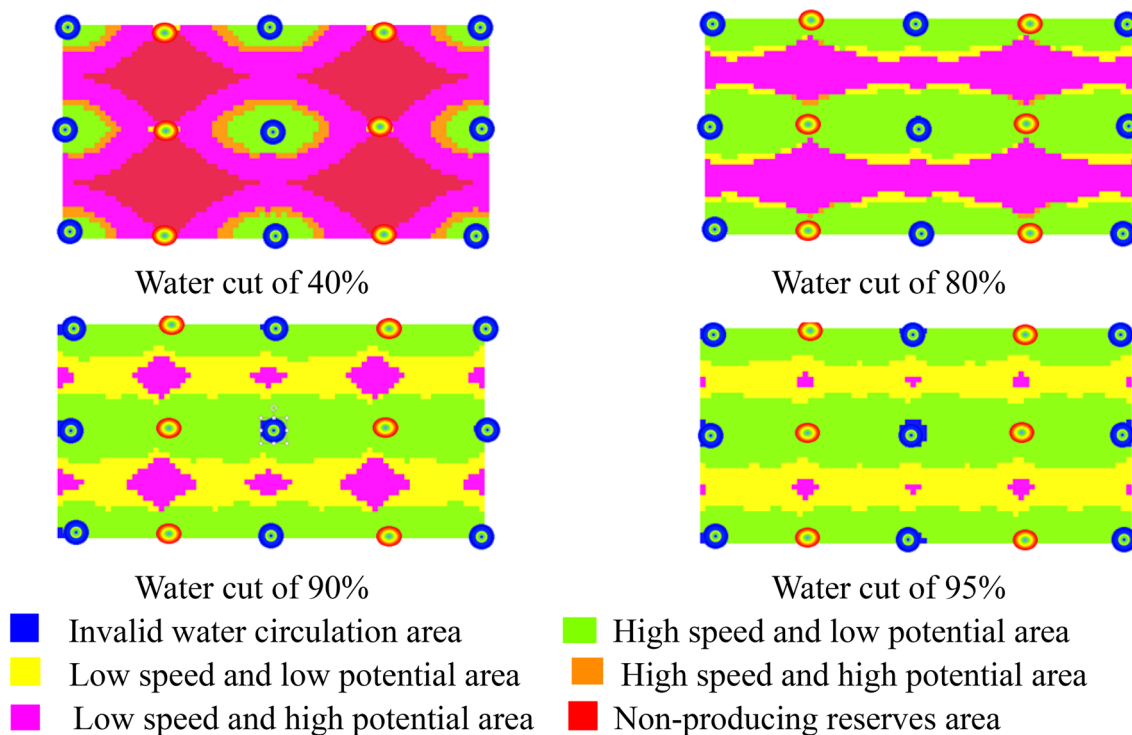


Fig. 5 Seepage field partition diagram of line well pattern

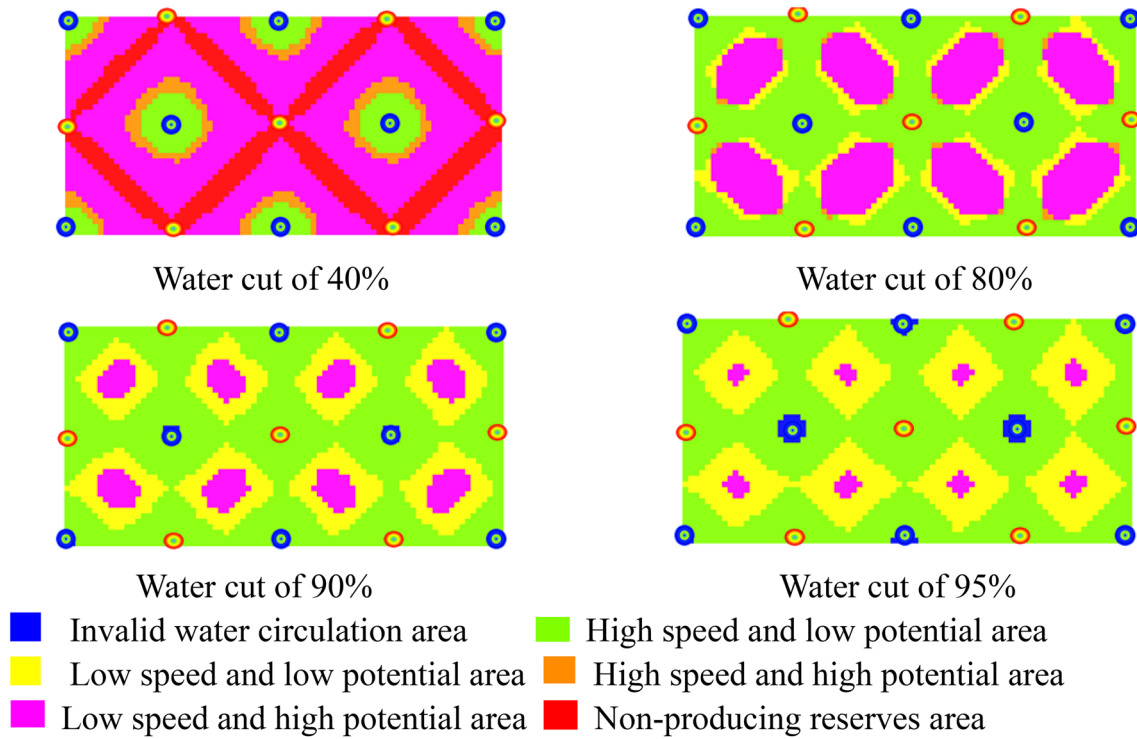


Fig. 6 Seepage field partition diagram of five spot pattern

and low potential area appeared as belts. These areas are also the key areas for potential exploitation of reservoirs in the high water cut period.

For a five spot well pattern at the early stage of development, the non-producing reserves area exists between the water wells, and high speed and low potential area is first formed near the water wells. With the increase of water cut, the low velocity and high potential area only exists between the oil wells or the water wells. When the water cut reaches 95%, the invalid water circulation area forms near the water wells.

The evolution law for the seepage field under different reservoir heterogeneities is studied. A horizontal permeability model and an oblique permeability model are designed. As shown in Fig. 7, the permeability ratio is 10 and the injection production pressure difference is 1 MPa.

For the horizontal permeability model in the low water cut stage, the low permeability area forms a non-producing reserves area. With the rising water cut, the high permeability area forms a continuous highspeed seepage area, while the low permeability area still has great potential. When the water cut reaches 95%, with the increase of permeability value, the area of low speed and high potential gradually decreases and is distributed in a scattered manner between the wells (Fig. 8).

For the oblique permeability model in the low water cut stage, the invalid water circulation area first appears in the middle–low permeability position. With the increase in water cut, high speed and low potential area is formed near the oil or water wells. The low permeability region retains a large volume of the remaining oil and forms the low speed and high potential area. When the water cut reaches

Fig. 7 Schematic diagram of different permeability reservoirs

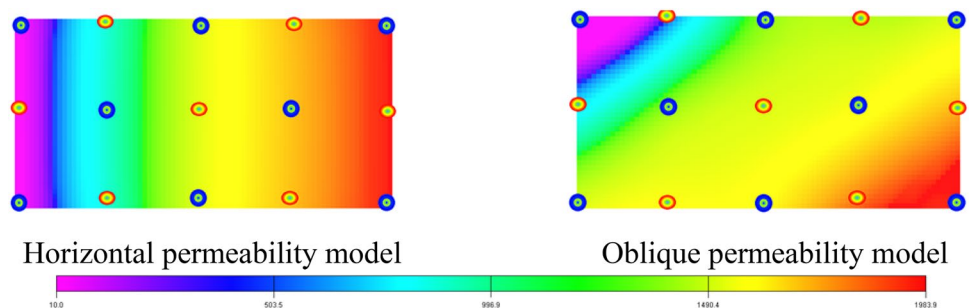
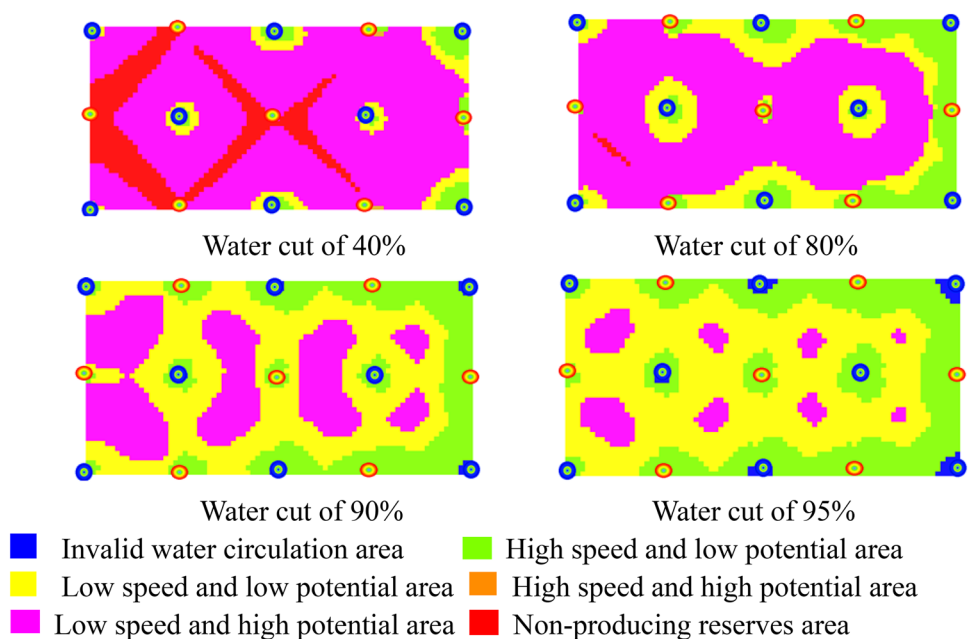


Fig. 8 Seepage field partition diagram of horizontal permeability model

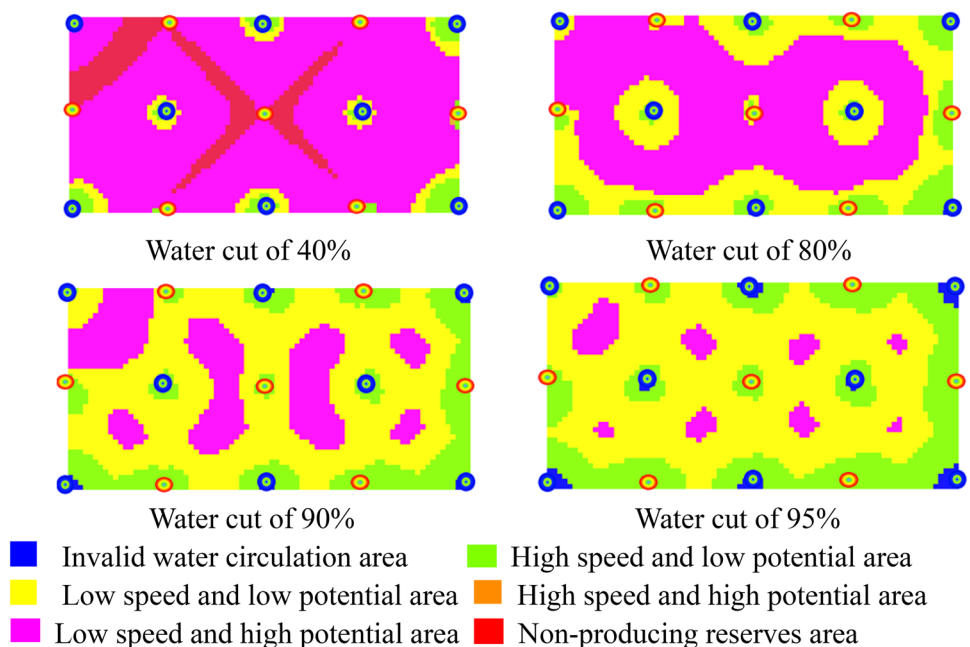


95%, the low permeability area forms a large number of low speed and high potential areas due to the low water flooding degree, a small amount of low speed and high potential reservoir is distributed in the high permeability region (Fig. 9).

We compare the area ratio of various water cut stages under different well patterns and heterogeneities. In the case of high water cut and a perfect well pattern, high speed and low potential area and low speed and low potential area occupy most of the reservoir. Although the low speed and high potential area is small, it is still the key position for the recovery of the remaining oil in the late

period of development. At the same time, in the process of development, the invalid water circulation area should be determined in time to prevent the formation of a predominant percolation channel.

Fig. 9 Seepage field partition diagram of oblique permeability model



Study on the method of reconstructing the seepage field

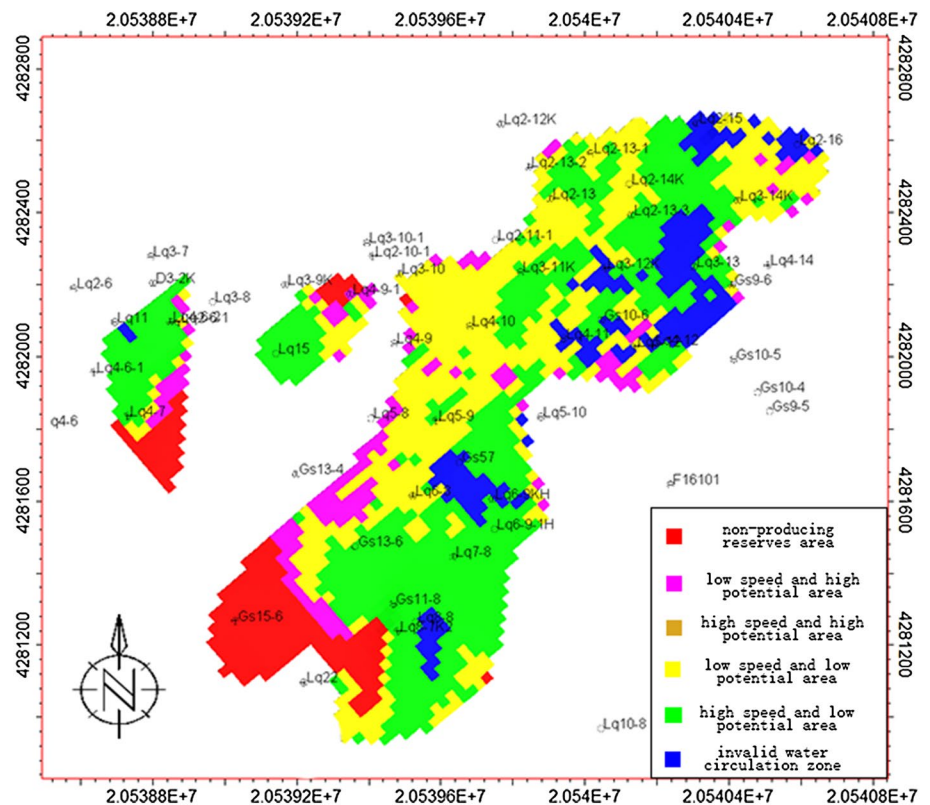
The different characteristics of a reservoir seepage field in the high water cut period are taken into consideration, and the different adjustment measures are put forward with the objective of flow field balance. For the ineffective water circulation area, we closed the water wells or converted the development to reduce the flow intensity in the region. For the non-producing reserves area, we expanded the fluid sweep region through increasing the number of wells. We maintain the current displacement speed development in the low speed and low potential area. By improving the displacement speed properly, the low speed and high potential area can be maintained with efficient development. For the high speed and low potential area, it is necessary to reduce the displacement speed and maintain economic and effective development in the case of the formation of a predominant percolation channel. A stable and effective flow field can be formed by reducing the displacement speed properly in the high speed and high potential area. Through the above adjustment method, the aim of balancing the flow field and improving the development effect is achieved.

Study on the evaluation and reconstruction of seepage field in the high water cut period of Gang Dong oilfield

The Gang Dong oilfield is located in the middle part of the Huang Hua depression. It is divided into two sets of layers. The average permeability is $800 \times 10^{-3} \mu\text{m}^2$, which corresponds to a typical medium–high permeability reservoir. To date, the comprehensive water cut has reached 95.68%, and the recovery degree has reached 43.18%. At present, there are many problems such as high water consumption, low water storage rate and difficulty in subsequent development.

We use the seepage field classification method to evaluate the Nm3-4-1 layer of the Gang Dong oilfield, as shown in Fig. 10. Because of the incomplete flood pattern, the producing degree of crude oil in the Gs15-6 well area in the southwest of this layer is low and forms a non-producing reserves area. In the Lq2-15, Lq2-16 and Lq3-13 well area, an ineffective water circulation area is formed because of the high water consumption. There are still some low velocity and high potential areas in the Lq5-8 well area, which is located at the high part of the structure. Low speed and low potential area is mainly located at the high part of the structure. With the influence of edge water invasion, high speed and low potential area is formed in the low part of the structure.

Fig. 10 Gang Dong oilfield Nm3-4-1 layer seepage field schematic diagram before adjustment



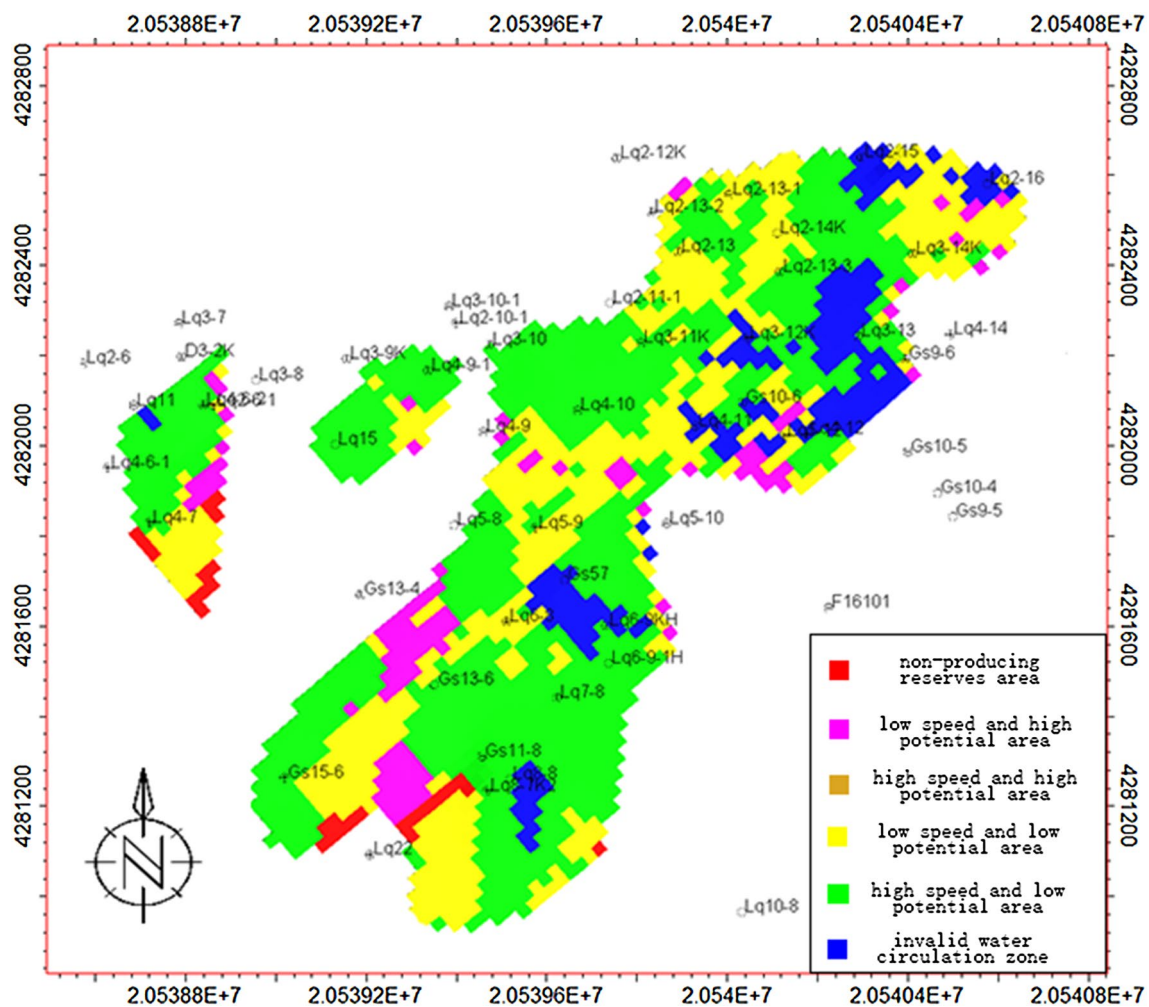


Fig. 11 Gang Dong oilfield Nm3-4-1 layer seepage field schematic diagram after adjustment

Table 3 Comparison of parameter predictions before and after adjustment of the Nm3-4-1 layer seepage field

Water cut (%)		Accumulation of oil production, million tons	
Before adjustment	After adjustment	Before adjustment	After adjustment
95.3	91.5	49.1	58.6
Residual oil saturation, decimal		Variation coefficient of seepage field, decimal	
Before adjustment	After adjustment	Before adjustment	After adjustment
0.42	0.35	0.96	0.63

According to the above evaluation and adjustment method, we optimize the oil and water wells of the Nm3-4-1 layer in the Gang Dong oilfield, and compare the development effect before and after the optimization. The adjusted reservoir seepage field is shown in Fig. 11. After

the adjustment, the seepage flow field is more balanced, the coefficient of variation is reduced by 0.33; the water cut is reduced by 3.8%; the accumulation of oil production is increased by ninety-five thousand tons and the development effect is obviously improved (Table 3).

Conclusion

1. According to two-phase flow theory combined with the seepage characteristics of a high water cut reservoir, an evaluation system for the seepage field is established, and the reservoir is divided into six seepage field types. Each unit reflects the development potential of the reservoir, including both the historical and current stages. The evaluation method provides a theoretical basis for the exploitation of the residual oil in the high water cut development period.
2. The adjustment of the flow field is different in each percolation unit. In the process of reconstructing the flow field in the high water cut period, the non-producing reserves area and the low speed and high potential area are the key areas for exploiting the remaining oil. At the same time, to prevent the ineffective channeling of injected water, measures such as plugging or changing the development mode should be carried out in time before the formation of the ineffective water circulation area.
3. The evaluation of the seepage field can effectively reflect the potential of each area and the evolution of the flow field, which reveals the distribution characteristics of the remaining oil in the high water cut period.

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