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A New Method for Clarifying the Water Breakthrough Rule of Horizontal Wells in the Bottom-water Oil Reservoir and Field Application

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ABSTRACT

Attributes is highly heterogeneous along horizontal wells and the water breakthrough mechanism is complex in the bottom-water oil reservoir. The conventional numerical and physical simulations are laborious and have a limited contribution to on-site water plugging operations. This paper presents an effective method for clarifying the water breakthrough rule of horizontal wells. Firstly, the water drive mathematical model of the heterogeneous production area was constructed by analyzing well-logging curves. Secondly, the adaptive iterative algorithm was adopted to realize the prediction of the water breakthrough parameters along horizontal wells, based on the non-piston water drive theory. Finally, the validity of the innovative model is verified through comparison with a rigorous physical simulation experiment. The results show that the water breakthrough time difference along the horizontal well and the water cut stage height of the single well are positively correlated with the permeability differential. The permeability differential is negatively correlated with the utilization degree of low permeability area. The increase of the area of the high permeability section delays the water breakthrough time and has a great influence on the water cut of single well. With the increase of water avoidance height in high permeability area, the water breakthrough time of oil well is delayed, and the height of water cut stage of single well is reduced. Finally, taking a horizontal well of an oilfield in Bohai Bay as an example, this paper clarifies the water breakthrough rule of the 9th member of the horizontal well and identifies more remaining oil in the first and 4th members. This research has an important theoretical instructional significance to formulate reasonable single well control water plugging measures.

Keywords: Bottom-water oil reservoir; Horizontal well; Adaptive iteration; Water breakthrough rule

[1]

NONMENCLATURE

Symbols	
ρ	Density, kg/m^3
v	Flow rate, m/s
ϕ	Porosity
V	Pore volume, m^3
S	Saturation
K	Permeability, mD
p	Transient pressure, MPa
μ	Viscosity, mPa·s
h	Water avoidance height, m
Q	Production, m^3/s
L	Length of horizontal zone of horizontal well, m
W	Cumulative injection, m^3
A	Flow cross-sectional area, m^2

1. INTRODUCTION

Bottom-water reservoirs are widely distributed in the coastal areas of China. The bottom water energy of an oilfield in Bohai Bay is sufficient, and the heterogeneity along the horizontal well is serious. At present, the comprehensive water cut of the oilfield is 95.5%, but the recovery degree is only 11.5%. In the development process of this kind of reservoir, the problem of fast water breakthrough and low production rate along the horizontal well arises. Formulating reasonable water breakthrough identification and water control and plugging methods for the production section of horizontal wells is a key factor for the efficient development of the bottom-water reservoirs. At present, the main methods for studying the water breakthrough mechanism along the horizontal well in bottom-water oil reservoirs are physical simulation,

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numerical simulation, semi-analytical and analytical solution.

Pemadi and Wibowo[1-2] used physical simulation method to study the change rule of water crest along horizontal wells with crude oil viscosity and reservoir thickness in bottom water reservoir and the influence of various factors on the productivity of horizontal wells. Liu Li et al. employed the planar sintering simulation method to investigate the evolution pattern of water coning in bottom-water reservoirs in the presence of interlayers [3]. Wang et al. utilized modern electronic imaging surveillance technology and flow testing techniques to construct a two-dimensional physical simulation system to observe the progression of bottom water crest in horizontal wells[4]. Ren[5] et al. improved the two-dimensional visual physical simulation experimental apparatus for horizontal wells, enabling the monitoring of bottom-water advancement and oil-water movement throughout the entire experimental process. Huang[6] et al. utilized flow testing technology, radiographic imaging technology, and numerical control devices to establish a large-scale three-dimensional physical model of horizontal wells and observed the progression of the water crest at the bottom of the horizontal wells. Building upon the work of Huang, Liu et al. conducted research on the formation and development mechanisms of water crests in planar heterogeneous bottom-water reservoirs[7]. Li[8] et al. considered the effects of wellbore trajectory, wellbore pressure drop, and reservoir heterogeneity on the location and development characteristics of bottom water crests. Although physical simulation methods allow for direct observation of the bottom water rise process along horizontal wells, the complexities of subsurface formations and well trajectory models cannot be simulated. Hu[10] et al. utilized numerical simulation methods to investigate the dynamics of water breakthrough under the influence of various factors, taking into account wellbore pressure drop. Ren et al. developed a numerical simulation model at the experimental scale, and the simulated results showed discrepancies compared to the physical simulation experiments.[11]. Due to the impact of computational speed, most of the aforementioned numerical simulation methods find it challenging to account for the complexities of the reservoir formations and the intricate fluid flow mechanisms. Lu[12] analyzed several mathematical models of bottom water entering the wellbore along horizontal wells and compared the adaptability of these models. Wang[14] et al. proposed a mathematical model for the production dynamics of horizontal wells in bottom water oil reservoirs. This model comprehensively considers the interaction between two-phase oil-water flow in the wellbore and porous media flow, analyzing the impact of wellbore pressure drop on parameters such as water-free oil recovery and water breakthrough time along horizontal wells. The semi-analytical and analytical solution methods can account for complex flow mechanisms, but conventional solution approaches encounter difficulties in achieving resolution.

Based on field logging data and horizontal well trajectory data, this paper constructs a mathematical model for non-homogeneous water drive in the production stage of bottom-water oil reservoirs along horizontal wells. An adaptive iterative method is employed to solve the model, enabling rapid prediction of water breakthrough patterns along horizontal wells. This approach effectively transforms geological data into production data, providing significant guidance for water control and water plugging operations in simple wells in the field.

2. PHYSICAL MODEL AND ASSUMPTIONS

Long-term tectonic movements and sedimentation processes have resulted in significant planar heterogeneity of the reservoir. The extensive reach of horizontal wells leads to significant along-path heterogeneity within the production section. Figure 1(a) shows a longitudinal profile of the production section along a horizontal well. The production section of the well passes through two sedimentary microfacies, heart beach bar and braided river channel, resulting in complex reservoir physical properties. To characterize the heterogeneity of the production section along a horizontal well in a bottom-water oil reservoir, a water drive physical model for the production section along the horizontal well was constructed, as shown in Figure 1(b). The basic assumptions of the model are as follows:

(1) Bottom water energy is infinite.

(2) Considering that the water avoidance height of the horizontal well is much smaller than the length of the production section along the horizontal well, the crossflow between each section is neglected.

(3) Non-piston water drive.

(4) Rigid porous media, incompressible viscous fluid.

(5) Darcy seepage.

(6) Neglecting capillary forces, gravity, and wellbore friction.

(7) Constant-rate liquid production.

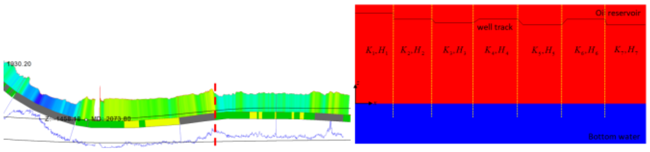


Fig. 1 Water drive physical model along the horizontal well in bottom-water oil reservoir

3. MATHEMATICAL MODEL AND SOLUTION

3.1 Flow source function construction

In the physical model of water drive in the production section along horizontal wells in bottom water oil reservoirs, neglecting the intersegment crossflow, the bottom water rise process in each section along the *x*-direction of the horizontal well can be regarded as a one-dimensional two-phase flow. The continuity equations of oil phase and water phase are as follows:

The oil phase continuity equation:

$$-\frac{\partial}{\partial z}\left(\rho_o v_{oz}\right)=\frac{\partial}{\partial t}\left(\rho_o \phi S_o\right) \tag{1}$$

The water phase continuity equation:

$$-\frac{\partial}{\partial z}\left(\rho_w v_{wz}\right)=\frac{\partial}{\partial t}\left(\rho_w \phi S_w\right) \tag{2}$$

Given that the flow follows Darcy's law and neglecting capillary forces and gravity, the oil and water flow equations are as follows:

$$v_{oz}=-\frac{KK_{ro}\left(S_w\right)}{\mu_o}\frac{\partial p_o}{\partial z} \tag{3}$$

$$v_{wz}=-\frac{KK_{rw}\left(S_w\right)}{\mu_w}\frac{\partial p_w}{\partial z} \tag{4}$$

Under initial conditions, the oil reservoir pressure and oil saturation are uniformly distributed:

$$p\big|_{t=0,z=h}=p_i \tag{5}$$

Inner boundary condition：

$$\left.\frac{\mathrm{d}p}{\mathrm{d}z}\right|_{z=h}=\frac{Q}{2KLR\left(\dfrac{K_{ro}}{\mu_o}+\dfrac{K_{rw}}{\mu_w}\right)} \tag{6}$$

3.2 Mathematical model solution

3.2.1 Discrete segmentation processing

According to equations (3) and (4), integrating along the *z*-direction yields the production rate equations for each section along the horizontal well.

$$Q_i=\frac{K_i A_i \Delta p_i}{\displaystyle\int_0^{z_{fi}}\frac{1}{\dfrac{K_{ro}}{\mu_o}+\dfrac{K_{rw}}{\mu_w}}dz+\mu_o\left(H_i-z_{fi}\right)} \tag{7}$$

（1）Before water breakthrough in the *i*-th section along the horizontal well:

$$z_{fi}=f_w^{'}\left(S_{wf}\right)\frac{\int_0^t Q_i dt}{A_i\phi} \tag{8}$$

$$R_{bi}=\left[\frac{W_i}{\phi A_i}\int_{S_{wc}}^{S_{wf}}\frac{f_w^{''}\left(S_w\right)}{\dfrac{K_{ro}}{\mu_o}+\dfrac{K_{rw}}{\mu_w}}dS_w+\mu_o\left(H_i-z_{fi}\right)\right]/\left(K_i A_i\right) \tag{9}$$

$$Q_{oi}=Q_i \tag{10}$$

（2）After water breakthrough in the *i*-th section along the horizontal well:

$$H_i=f_w^{'}\left(S_{wei}\right)\frac{\int_0^t Q_i dt}{A_i\phi} \tag{11}$$

$$R_{ai}=\left[\frac{W_i}{\phi A_i}\int_{S_{wc}}^{S_{wf}}\frac{f_w^{''}\left(S_w\right)}{\dfrac{K_{ro}}{\mu_o}+\dfrac{K_{rw}}{\mu_w}}dS_w\right]/\left(K_i A_i\right) \tag{12}$$

$$Q_{oai}=V_i\times\Delta\overline{S_i} \tag{13}$$

Due to the constant liquid production rate of the horizontal well,

$$Q_1\times R_1=Q_2\times R_2=\cdots=Q_n\times R_n \tag{14}$$

3.2.2 Pretreatment of relative permeability and saturation

In order to solve the integral term in equation (7), the Corey model[16] is used to process the relative permeability curve.

Based on the principle of least squares, fitting limits for oil phase and water phase relative permeability curves are set separately. The optimal values for n_o and n_w are obtained and corresponding relative permeability curves are generated, as shown in Figure 2.

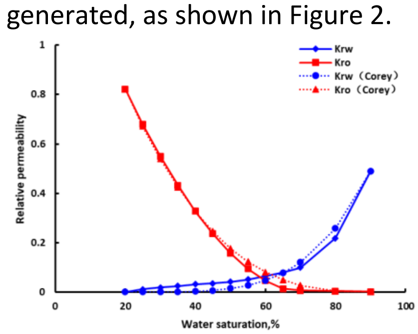


Fig. 2 Relative permeability curve treated by Corey

Based on the principle that the first derivative of the water cut at the front edge of the water drive equals the slope of the water cut curve, a target function is constructed. By solving for the zero point of the target function, the water saturation at the front edge of the water drive before breakthrough is ultimately obtained.

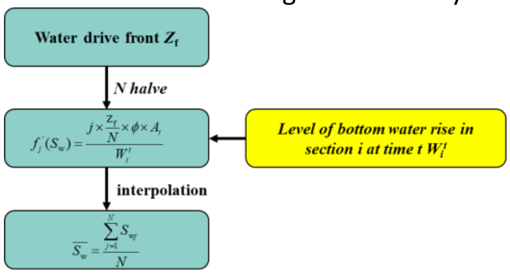


Fig. 3 Principle of calculating average water saturation

3.2.2 Adaptive iterative solution method

Horizontal well production sections in bottom water oil reservoirs exhibit complex geological characteristics, with significant fluctuations in longitudinal depth of the well trajectory. On one hand, the distribution of permeability in the production section is complex, making it difficult to calibrate the parameter matrix required for the solution process. This leads to challenges in accurately determining the water breakthrough stages in each section. On the other hand, solving for fixed time steps does not accurately determine the water breakthrough moments in each section. This leads to errors in calculating the parameters at those specific moments, and these errors accumulate as the iteration steps increase. Therefore, conventional iterative methods are no longer applicable. This paper proposes an adaptive iterative solution method that effectively addresses the aforementioned issues.

Firstly, the logging data and well trajectory of the horizontal well production section are imported to obtain the permeability parameter matrix ***K***, the water avoidance height parameter matrix ***H***, and the permeability zone length parameter matrix ***L***.

The analysis of equations (8) and (14) shows that there is a positive correlation between the water breakthrough time and the ratio of permeability to the square of the water avoidance height.

$$t_{\mathrm{wb}} \propto \frac{K}{H^2} \tag{15}$$

Then, according to the order of water breakthrough time, the parameter matrices of each section are sorted, and the permeability value, the water avoidance height, permeability zone length parameter matrix $\boldsymbol{K}'$, $\boldsymbol{H}'$, $\boldsymbol{L}'$, and are obtained after sorting.

Combining the above data with the post-processed relative permeability data, the initial flow resistance and daily liquid production for each section of the horizontal well can be calculated. Finally, the solution is obtained using time iteration. To accurately calculate the water breakthrough time for each section, this paper adopts an adaptive discrete time stepping iteration method. The process is as follows:

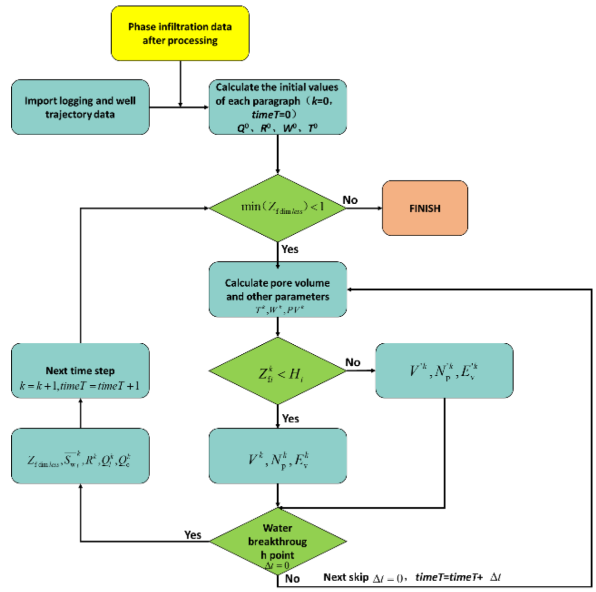


Fig. 4 Flow chart of adaptive Iteration

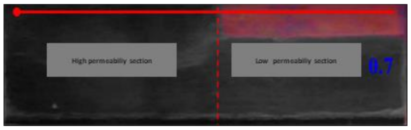
3.3 Mathematical model validating

In order to verify the reliability of this model, this chapter conducted physical simulation experiments on water breakthrough along a horizontal well in a bottom water oil reservoir under different crude oil viscosities and different permeability contrasts. By comparing the results of the experiment and the mathematical model, the reliability of the mathematical model is verified. The experimental scheme is shown in Table 1.

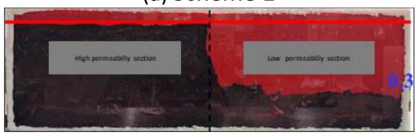
Table 1 Physical simulation scheme of water breakthrough along a horizontal well in the bottom water oil reservoir

Scheme	viscosity/mPa·s	Permeability contrast
1	4	3:1
2	4	5:1
3	50	5:1

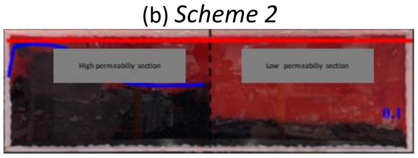
The experimental results are shown in Figure 5. The dimensionless bottom water heights for the low-permeability sections in the three schemes are 0.7, 0.3, and 0.1 respectively. This indicates that as the permeability contrast and crude oil viscosity increase, the degree of water movement in the low-permeability section decreases.



(a) *Scheme 1*



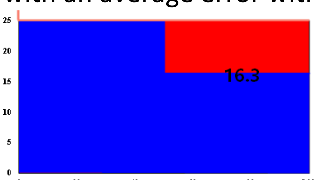
(b) *Scheme 2*



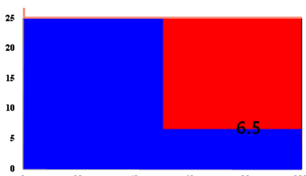
(c) *Scheme 3*

Fig. 5 Oil and water distribution along a horizontal well in the bottom-water oil reservoir under different experimental schemes

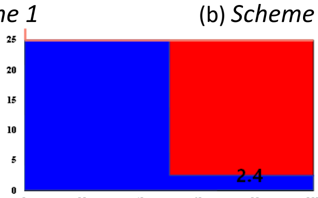
The parameters at the experimental scale were input into the water flooding mathematical model for solution, and the results are shown in Figure 6. The dimensionless rise heights of the bottom water in the low-permeability section are approximately 0.65, 0.26, and 0.10, respectively. The results of the physical simulation experiment confirm the reliability of the heterogeneous water drive mathematical model for the horizontal well production section in the bottom-water oil reservoir, with an average error within 10%.



(a) *Scheme 1*



(b) *Scheme 2*



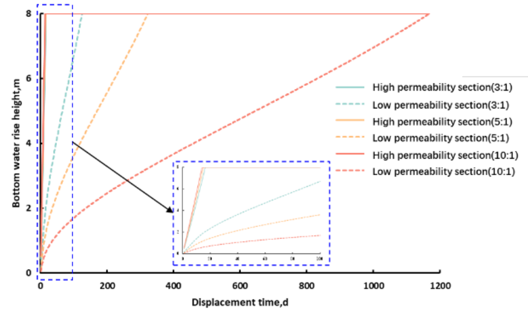
(c) *Scheme 3*

Fig. 6 Oil and water distribution in the water drive mathematical model along the horizontal well production section in bottom-water oil reservoir under different experimental parameters

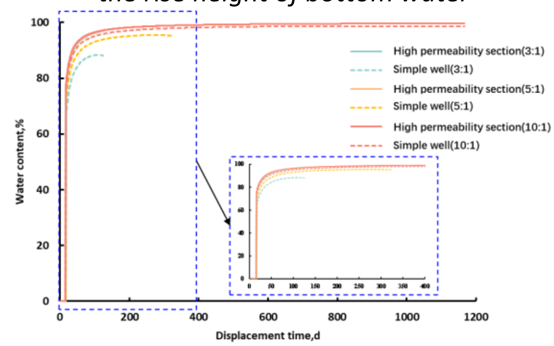
4. SENSITIVITY ANALYSIS

4.1 Permeability differential of production section

By varying the permeability values of the high permeability section in the horizontal well production section, setting the permeability contrast ratios at 3:1, 5:1, and 10:1, the impact of different permeability contrasts on the water breakthrough rule of horizontal wells is analyzed. The permeability value of the low permeability section is 1000 mD, the water avoidance height is 8 m, and the length of the permeability zone is 50 m. The results are as follows:



(a) *The influence of different permeability contrasts on the rise height of bottom water*



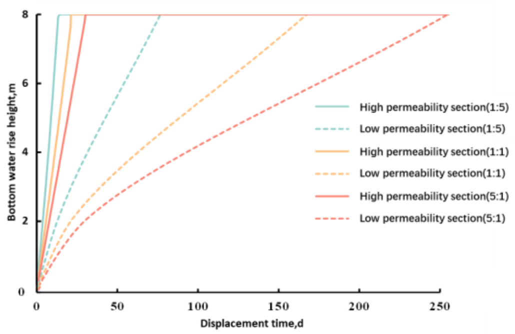
(b) *The influence of different permeability contrasts on water content*

Fig. 7 The influence of different permeability contrasts on dynamic data

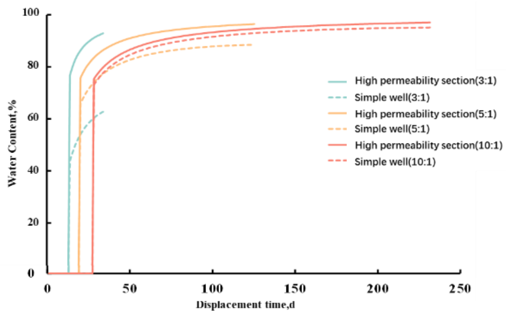
As shown in figure 7, the greater the permeability contrasts of the production section of the horizontal well, the earlier the water breakthrough time of the high permeability section, the later the water breakthrough time of the low permeability section, and the greater the water breakthrough difference between the sections; the height of water cut step in high permeability section is basically unchanged, but the higher the water cut step of single well is.

4.2 Permeability zone length of production section

The ratio of permeability zone length is set to 1:5,1:1 and 5:1. The length of the well is 120 m, the permeability *contrast* is 3:1, and the water avoidance height is 8 m. The results are as follows:



(a) *The influence of different permeability zone length ratio on the rise height of bottom water*



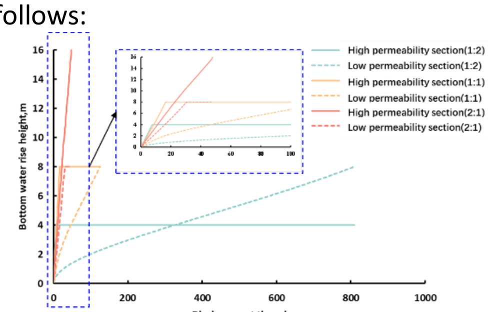
(b) *The influence of different permeability zone length ratio on water content*

Fig. 8 The influence of different permeability zone length ratios on dynamic data

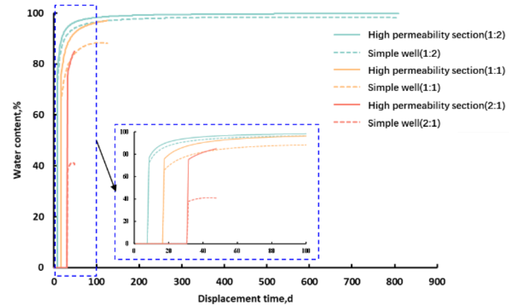
As shown in Figure.8, the longer the permeability section of the high permeability section, the later the water breakthrough time of the high permeability section and the water breakthrough time of the low permeability section. The overall water breakthrough time of the horizontal well is delayed, but the water cut step is higher.

4.3 Water avoidance height of production section

The water avoidance height ratios are set to be 1:2,1:1, and 2:1. The water avoidance height of the low permeability section is 8m, the permeability *contrast* is 3:1, and the permeability zone length is 50m. The results are as follows:



(a) *The influence of different water avoidance height ratio on the rise height of bottom water*



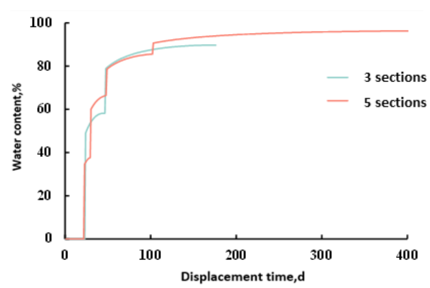
(b) *The influence of different water avoidance height ratio on water content*

Fig. 9 The influence of different water avoidance height ratios on dynamic data

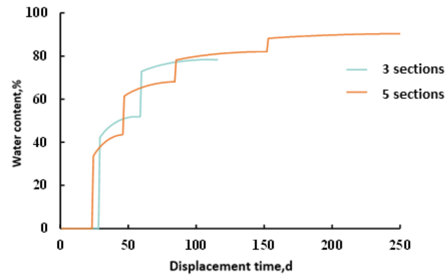
As shown in Fig.9, the larger the water avoidance height of the high permeability section is, the later the water breakthrough time of the high permeability section is, the earlier the water breakthrough time of the low permeability section is, and the smaller the water breakthrough difference between the sections is, which is more conducive to the formation of uniform displacement of bottom water. The water breakthrough time of single well is delayed and the water cut step is lower, which shows that when the water avoidance height of high permeability section is higher than that of low permeability section, it is more conducive to the water control and plugging operation of single well.

4.4 Number of heterogeneous sections in production section

The number of heterogeneous sections in the production section of the horizontal well is set to 3 and 5. The basic permeability is 1000mD (the permeability increment of the adjacent section is 1000mD), the basic water avoidance height is 8m (the water avoidance height increment of the adjacent section is 2m), and the length of the horizontal well is 150m.



(a) *Different permeability*



(b) *Different water avoidance heights*

Fig. 10 The influence of the number of heterogeneous segments on water cut of single well

As shown in Figure 10, the number of water content steps in the model is consistent with the number of heterogeneous sections. The permeability of the horizontal well production section and the water avoidance height have an effect on the water content of the single well, but the degree of influence is different.

5. FIELD APPLICATION

Taking well A of an oilfield in Bohai Bay of China as an example, the geological parameters of well A (Table 2) are obtained through the well logging curve and well trajectory data (as shown in Fig.11 and Fig.12). The geological parameters of the well are introduced into the heterogeneous water drive model of the horizontal well production section of the bottom-water oil reservoir established in this paper, and the water breakthrough rule of the horizontal well is predicted to guide the water control and plugging operation of the well.

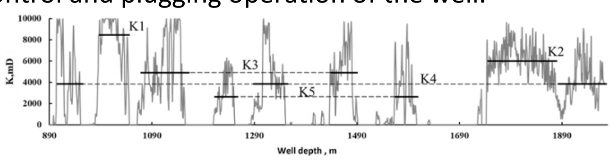


Fig. 11 The log curve of A well

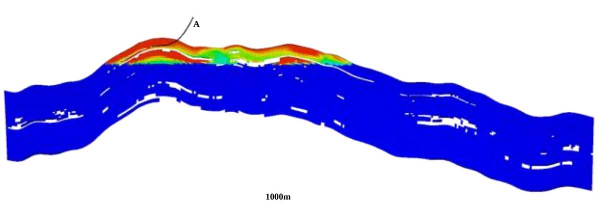
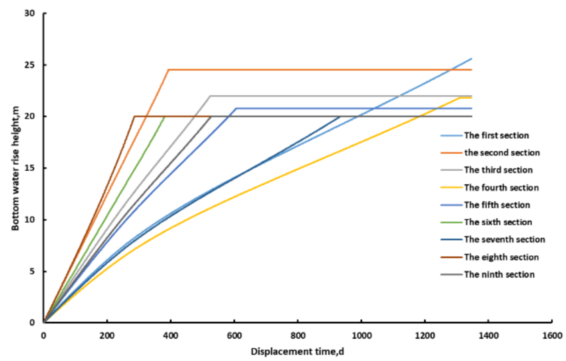


Fig. 12 The trajectory of A well

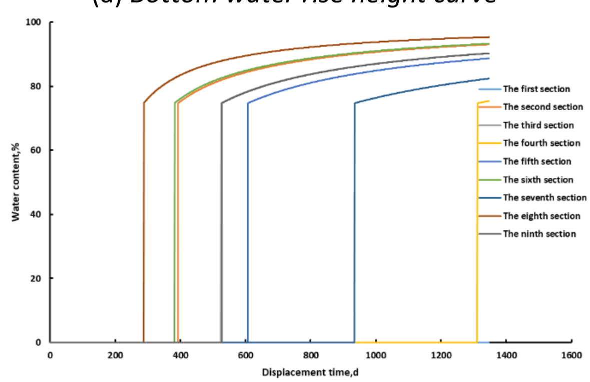
Table 2 Summary of geological parameters of A well

Well depth of production section /m	Permeability /mD	Water avoidance height /m
898~950	4220	25.6
980~1045	7536	24.5
1062~1154	5118	22.0
1210~1251	3104	21.8
1284~1350	4220	20.8
1437~1491	5118	20.0
1555~1606	3104	20.0
1743~1875	6204	20.0
1876~1972	4220	20.0

As can be seen from Table 2, the maximum permeability stage *contrast* in the production section of well A is 2.4:1, the maximum permeability zone length ratio is 3.2:1, and the maximum water avoidance height ratio is 1.28:1, showing weak heterogeneity (9 sections in total). The data in Table 2 were imported into the heterogeneous water drive mathematical model of the production section of horizontal wells in the bottom-water oil reservoir to predict the water breakthrough rule. The results are as follows:



(a) *Bottom water rise height curve*



(b) *Water content curve*

Fig. 13 Dynamic data of well A

As can be seen from Figure 13, there are 8 water content steps in different sequences of water breakthrough in each section of well A (there is A small difference between section 3 and section 9), and the height and length of the steps are different, indicating that in the production process, there are differences in the sequence of water breakthrough in well A, uneven use in the production section, and more remaining oil at the depth of well 898-950 and well depth of well 1210-

1251m. It has a certain potential of remaining oil exploitation.

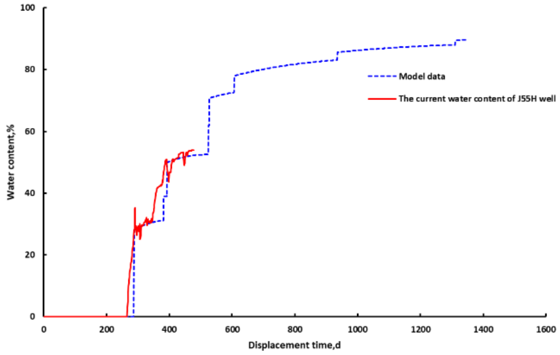


Fig. 14. Comparison of water content in A well

Combined with Fig.13 and Fig.14, it can be seen that the water cut of Well A rises slowly, and water has been seen in the second, sixth and eighth sections of the production section. The subsequent water control and plugging operations of the well need to be focused on.

6. CONCLUSION

(1) The new method proposed in this paper for predicting water breakthrough rule along horizontal wells in bottom-water oil reservoirs can efficiently transform geological data into production data. It facilitates the evaluation of the current water breakthrough condition along the horizontal well and forecasts the future trends in water breakthrough behavior.

(2) The greater the permeability contrast of horizontal well production section, the greater the difference of water breakthrough time, the higher the water content step, and the lower the utilization degree of low permeability section.

(3) The longer the permeability zone length of the high permeability section in the production section along the horizontal well, the later the water breakthrough time of the single well, but the higher the water content step.

(4) The higher the water avoidance height of the high permeability section in the production section of the horizontal well, the later the water breakthrough time of the single well and the lower the water content step.

(5) Taking Well A of an oilfield in Bohai Bay as an example, the water breakthrough rule of horizontal well is predicted. The results show that the water cut of well A rises slowly, and there are 8 water content steps with different length and height. In the production process, there are more residual oil in the 898-950 and 1210-1251 sections of the well depth. At present, the water has been seen in the second, sixth and eighth sections of the production section of Well A, and the second, sixth and eighth sections can be blocked in the water control and plugging operation.

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