Identification method of water-flooded layer based on analytic hierarchy process——Taking the Keshang Formation reservoir in the J188 well area as an example

LIU Wengfeng¹, ZHANG Xuyang¹, WANG Kang¹, YANG Yufeng¹, LIU Xin¹, ZENG Shuling², CHEN Jing²

¹Baikouquan Oil Production Plant, Xinjiang Oilfield Company, PetroChina, Karamay, 834000, China
²Tianjin Zhengfang Technology Development Co., Ltd., Tianjin, 300270, China

Abstract: Most oil fields in China have entered the high water cut stage, the identification of water flooded layers is a very important task. At present, the identification of water-flooded layers usually adopts the combination of qualitative method and quantitative method to carry out the work. However, the qualitative method is difficult to be characterized by quantitative numerical values, so the work efficiency is very low; the quantitative method needs to be taken in the actual operation. The oil-water relative permeability of the reservoir, the viscosity of the oil and water, and the original oil saturation, the calculation accuracy of these parameters are inevitably large errors. This paper explores a semi-quantitative method to overcome the insufficiency of qualitative methods, the simplification of quantitative parameters, and the error of water-flooded layer identification. The analytic hierarchy process was used to identify the water-flooded layer in the Keshang Formation reservoir in the 188 well area. The water production rate, oil saturation, production index and relative permeability index were integrated into a comprehensive water-flooded layer identification index. The results show that the total water-flooded layer identification coincidence rate reaches 70%. The method of water flooded layer identification based on analytic hierarchy process is feasible.

1. Preface
Most oil fields in China adopt the method of water injection development. After development for many years, all main oil layers have entered the stage of high water content. At present, the average water content of many oil fields has exceeded 80%, and some even exceed 90%. The water content of half oil production well has exceeded 60%[1]. Meanwhile, the oil-water relationship had become more and more complicated. In order to better predict the distribution of remaining oil and improve the recovery rate of old areas, it is a very important task to carry out the identification of water-flooded layers.

It is worth noting that in the process of water flooding, a series of changes have taken place in the reservoir from the macroscopic and microscopic perspective, including oil saturation, formation water salinity, porosity and permeability, rock wetting properties, fluid conductivity, oil displacement efficiency, formation pressure, etc., which are all changing[2]. These changes bring the possibility of identifying flooded layers and the changes of these multiple parameters, and increase complexity to the identification of flooded layers.
At present, the identification of water-flooded layers through convey is still a very important technical instrument. In comparison, convey types are diverse, the amount of collected data is large, and the captured formation information is rich, all of which can well reflect the physicochemical properties of rocks and fluid as well as changes in various parameters.

2. Research status of water-flooded layer identification

After scientific research for many years, various domestic oil fields and scientific research institutes have also developed their own unique methods in the interpretation of water-flooded layers. Daqing Oilfield has successively developed three kinds of methods for qualitative interpretation of water-flooded layers. (1) SP baseline deviation is mainly used to judge water-flooded layers[3], (2) multiple well measurement curves have been comprehensively used to classify the division of water-flooded layers[4-6], (3) on the basis of the second method, natural current and circular natural current convey have been added[7], so it can be said that the water flooded layer interpretation technology of Daqing Oilfield has reached the domestic leading level. Shengli Oilfield has developed a multi-functional analysis and interpretation technology for the interpretation of water-flooded formations, and China National Petroleum Exploration and Development Research Institute has developed the "Conventional Convey Data Interpretation Technology during Oilfield Waterflooding Development Phase" [8-11].

After 2000, on the basis of the predecessors' interpretation methods of these water-flooded layers, great improvements have been made in mathematical algorithms. There are automatic recognition methods based on neural networks[12-14], as well as algorithms of Boosting to improve BP neural networks[15], fuzzy statistics and gray recognition to evaluate flooded layers[16], water-flooded layer identification method based on feature selection and genetic algorithms[17], and water-flooded layer identification method based on decision tree[18].

Generally, for reservoirs with thick and homogeneous layers, the interpretation of water-flooded layers has been improved to be almost perfect. Conventional water-flooded layer identification methods fall into two categories including qualitative identification and quantitative identification.

2.1. Qualitative identification method of flooded layer

There are three methods that are widely used:

(1) Mudstone baseline deviation method

The layer with good physical properties in the same location is obviously flooded, and the SP curve baseline of the water-flooded layer is shifted.

(2) Radial resistivity comparison method

The deep and medium resistivity is basically overlapped, and the negative and deep resistivity shows negatively different. The stronger the water flooding is, the lower the absolute resistivity will be reduced.

(3) Dielectric constant and depth resistivity intersection diagram method

The dielectric constant and phase angle of water are very large, which are several times or tens of times that of rock matrix and oil and gas. After the oil layer is flooded, its relative dielectric constant and phase angle increase significantly. The phase difference curve overlaps with the neutron porosity curve, and they move in opposite directions in the oil section, and the higher the oil saturation of the formation, the greater the difference in amplitude between them; while in the water layer and mudstone, their trends are identical.

2.2. Quantitative identification method of water-flooded layer

At present, the quantitative identification method of water-flooded layer is mainly used to carry out the classify water-flooded level, and there are three main categories including water production rate method, oil displacement efficiency method and mining index method.

(1) Water production rate method
\[
F_w = \frac{Q_w}{Q_w + Q_o} = \frac{1}{1 + B \cdot \frac{K_{ro} \mu_w}{K_{rw} \mu_o}} \rightarrow (1)
\]

where, \(Q_w\) and \(Q_o\) denote the partial flow of oil phase and water phase, respectively;
\(K_{ro}\) and \(K_{rw}\) denote the relative permeability of oil and water respectively;
\(\mu_o\) and \(\mu_w\) denote the viscosity of oil and water respectively;
B denotes lithology parameters.

According to the standards stipulated by the former China National Petroleum Corporation, \(F_w\) shall be used to subdivide the water flooding level of the oil layer into the following 5 categories.

\([0, 10\%)\) is the oil layer, \([10\%, 40\%)\) is the weak water flooding, \([40\%, 60\%)\) is medium water flooding, \([60\%, 80\%)\) is strong water flooding, \([80\%, 90\%)\) is relatively strong water flooding, and \([90\%, 100\%)\) is extremely strong flooding.

(2) Oil displacement efficiency method
\[
\eta = \frac{S_w - S_{wb}}{1 - S_{wb}} \rightarrow (2)
\]

where, \(S_w\) denotes the current water saturation of the flooded oil layer;
\(S_{wb}\) denotes the original bound water saturation of the flooded oil layer.

(3) Mining index method
\[
F_{ow} = \frac{S_o - S_o'}{S_o} \rightarrow (3)
\]

where, \(S_o\) denotes current oil saturation of water flooded oil layer;
\(S_o'\) denotes the original oil saturation of the flooded oil layer.

(4) Relative permeability index method
\[
K_{of} = (K_{ro} - K_{rw}) \frac{K_{ro}}{K_{rw}} \rightarrow (4)
\]

where, \(K_{ro}\) denotes relative permeability of oil phase;
\(K_{rw}\) denotes relative permeability of water phase.

2.3. Limitations of current methods for identifying flooded layers

As regards the qualitative method for identifying the flooded layer mentioned above, although it is easy to obtain the value of the convey curve, the identification result of the water-flooded layer is difficult to be characterized by quantitative values. The quantitative method for the identification of the water-flooded layer is very accurate in principle, but it is required to obtain the relative oil-water permeability of the reservoir, the viscosity of oil and water, and the original oil saturation in actual operation. The calculation accuracy of these parameters inevitably exhibits large errors. Taking oil saturation for example, even the original reservoir that has not been developed, in the same reservoir, different parts (oil saturation zone, oil unsaturated zone, fluid two-phase motion transition zone, residual oil saturation transition belt) has different oil saturation. After the reservoir water injection development, oil and water distribution have become very complicated, especially in areas with strong heterogeneity, and for reservoirs with complex pore throat structure, the difference in oil saturation of different parts is even larger.

The current qualitative and quantitative methods are quite different in thinking. The qualitative method probes the deviation and change of natural potential and resistivity logging curves, while the quantitative method probes water production or oil saturation. This paper explores a semi-quantitative method to overcome the difficulty of quantification by qualitative methods. The quantitative method uses a single quantitative parameter to evaluate the deficiencies of water-flooded layers and reduce the error of water-flooded layers identification.
3. Application of analytic hierarchy process in the identification of water-flooded layers in the keshang formation oil reservoir in the area with 188 wells.

3.1. Basic principles and working steps of AHP
Analytic Hierarchy Process (AHP) is an effective method of semi-quantitative decision-making and calculation. This method was proposed by American operations researcher Saaty in the early 1970s[19-20], which built a complex quantization issue into an orderly hierarchical structure, and judged the weights of various evaluation targets under different criteria by comparing them one by one, so that each evaluation target was quantified and sorted. The core problem of the entire evaluation process is to calculate the importance coefficient of each evaluation target relative to each criterion. There are several important basic weight methods including ring weighting method, fixed weighting method, direct weighting method, function formation weight method, variance information weighting method, related information weighting method, and entropy weight method, etc.

General steps of AHP:
(1) Establish a hierarchy structure
When using AHP to analyze and solve problems, sort and divide the problem into several levels at first, take the core problem that needs to be solved as the highest level, that is, the target level, and use the judgment basis composed of multiple parameters as the intermediate level that is the criterion layer, take the judgment target as the lowest level, that is, the evaluation level. The number of levels in the structure can be appropriately increased or decreased according to the complexity of the problem. Generally, the number of single levels does not exceed 9.

(2) Establish a judgment matrix
The importance of the highest level relative to the intermediate level is valued. The methods of valuation include subjective and objective ones. In order to avoid errors, the judgment elements of the intermediate level are compared with each other and scored according to importance, and the judgment matrix of the intermediate level is formed according to the scoring result.

(3) Consistency test
Use yaahp software for consistency test to ensure the rationality of the judgment matrix, then calculate the weight of the intermediate level.

3.2. Basic characteristics of the Keshang Formation reservoir in Well 188
The Keshang Formation reservoir in the Jian188 area is a monoclinic structure reservoir with fault blocking. The average sediment thickness is 78m, which is braided river facies deposit on the edge of the flood plain near the foothills. The lithology of the oil-bearing layer is mainly composed of giant-medium fine sand and small conglomerate, with an average porosity of 15% and a permeability of 74.5 × 10^{-3} μm². It belongs to the second-class reservoir of medium permeability sand and conglomerate. The lithology of the Keshang Formation reservoir in the 188 well area can be divided into unequal grain conglomerate, unequal grain small-medium conglomerate, unequal grain fine-small conglomerate, fine conglomerate, coarse sandstone, medium and fine sandstone and other six lithologies. There are many types of lithology (25 types). In order to facilitate the evaluation of water-flooded layers, the lithology is sorted and summarized into sandstones and conglomerates, and the interpretation of water-flooded layers is carried out according to sandstones and conglomerates.

3.3. The process and results of water flooded layer identification
According to the relevant elements of the flooded layer, the hierarchy is divided as follows:
Among them, the identification of the flooded layer is the highest layer, and the identification of the flooded layer in each section is carried out for specific situations. $F_w$, $S_o$, $F_{ow}$, and $K_{rf}$ are the intermediate layers, which are the key indicators for judging and quantifying the flooded layer. $F_w$ denotes water production rate, $S_o$ denotes oil saturation, $F_{ow}$ denotes mining index, and $K_{rf}$ denotes relative permeability index. Weak flooding, medium flooding, moderate to strong flooding and strong flooding are the bottom layers and the final program for dividing the flooding levels of each section.

According to the development experience of the Keshang Formation oil reservoir in Well 188, through expert scoring method, the parameters of the intermediate level are compared with each other, and the judgment matrix of the highest layer relative to the intermediate level is obtained as below:

\[
\begin{array}{|c|c|c|c|c|}
\hline
 & F_w & S_o & F_{ow} & K_{rf} \\
\hline
F_w & 1 & 3 & 1 & 2 \\
S_o & 1/3 & 1 & 1/3 & 2 \\
F_{ow} & 1 & 3 & 1 & 2 \\
K_{rf} & 1/2 & 1/2 & 1/2 & 1 \\
\hline
\end{array}
\]

Using yaahp software for consistency test, $0.0579 < 0.1$, it passes the consistency test.

The result of calculating the weights of the judgment matrix using arithmetic average and geometric average is:

| Table 1 Water flooded layer identification parameter weight calculation table |
|-------------------------------|---|---|---|---|
| Method | w1 | w2 | w3 | w4 |
|-------------------------|---|---|---|---|
| Arithmetic average | 0.348 | 0.164 | 0.348 | 0.141 |
| Geometric average method | 0.355 | 0.156 | 0.355 | 0.135 |
| Result | 0.35 | 0.16 | 0.35 | 0.14 |

From the calculation results of the weights of the identification parameters of the flooded layer, it can be seen that the water production rate and production index have the greatest impact on the quantitative identification of the flooded layer, followed by the effects of oil saturation and relative permeability index.

According to the intersection graph of oil-water relative permeability, water production rate and water saturation of the Keshang Formation oil reservoir and gravel stone in the Well 188 area as well as the intersection graph of water production rate and production index, the quantitative plot of each evaluation parameter can be obtained.
Fig. 2 Cross-section of oil and water relative permeability, water production rate and water saturation in sandstone layer

Fig. 3 Cross-flow diagram of oil-water relative permeability, water production rate and water saturation in conglomerate
Table 2 Identification table for quantitative indicators of water-flooded layer identification

| flooded grade      | Sandstone | Sandstone | conglomerate | Sandstone | conglomerate |
|--------------------|-----------|-----------|--------------|-----------|--------------|
| oil layer          | ≤10       | ≤10       | ≥60          | ≥59       |
| Weak flooding      | 10~40     | 10~40     | 60~55        | 59~54     |
| Flooding medium    | 40~70     | 40~70     | 55~50        | 54~49     |
| Strong flooding    | ≥80       | ≥80       | ≤50          | ≤49       |

| flooded grade      | Sandstone | Sandstone | conglomerate | Sandstone | conglomerate |
|--------------------|-----------|-----------|--------------|-----------|--------------|
| oil layer          | ≤5        | ≤4        | ≥0.8         | ≥0.7      |
| Weak flooding      | 5~15      | 4~14      | 0.8~0.02     | 0.7~0.016 |
| Flooding medium    | 15~25     | 14~24     | -0.02~0.03   | -0.016~0.017 |
| Strong flooding    | ≥25       | ≥24       | ≤0.035       | ≤0.009    |

According to the weights calculated by the judgment matrix and the quantitative indicators obtained for each parameter, a comprehensive indicator for identifying the flooded layer can be obtained:

\[ F_{\text{flooding}} = 0.35F_w' + 0.16S_o' + 0.35F_{ow}' + 0.14K_{rf}' \] (5)

Where, \( F_{\text{flooding}} \) is a comprehensive index for identifying flooded layers
\( F_w' \) is a quantitative indicator of water production rate
\( S_o' \) is a quantitative indicator of oil saturation
\( F_{ow}' \) is a quantitative indicator of the mining index
\( K_{rf}' \) is a quantitative indicator of relative permeability index

According to the calculation result of the flooding layer identification index \( F_{\text{waterflooding}} \), (0, 0.25] is the oil layer, (0.25, 0.5] is the weak water flooding, (0.5, 0.75] is the middle water flooding, while (0.75, 1] is the strong water flooding.

The following is the evaluation results:
Table 3 Water flooded layer evaluation results table

| Well number | Liquid production profile test |
|-------------|--------------------------------|
| Test result | Layer number                  |
| 19          | strong flooding 35            |
|             | Flooding medium 10           |
|             | Weak flooding 13             |

Interpretation results of flood level

|                | Coincidence rate (%) | Total average Coincidence rate |
|----------------|----------------------|-------------------------------|
| strong flooding| 77.1%                |                               |
| Flooding medium| 70.0%                |                               |
| Weak flooding  | 61.5%                | 70.0%                         |

4. CONCLUSION

(1) The water flooded layer identification method based on the analytic hierarchy process integrates the water production rate, oil saturation, mining index and relative permeability index into a comprehensive water flooded layer identification index, which overcomes difficulties in practical application of the conventional qualitative and quantitative methods. On one hand, it improves work efficiency. On the other hand, human-induced errors are avoided.

(2) Through comparison and analysis with the results of the liquid production profile test, the conforming rate of the strong water flooded layer reaches 77.1%, the conforming rate of the intermediate water flooded layer reaches 70.0%, and the conforming rate of the weak water flooded layer reached 61.5%. The total conforming rate of the identification of the flooded layer reaches 70%. The identification method of flooded layer based on analytic hierarchy process is feasible, and the identified flooded layer is of high credibility.

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