A New Method of Predicting the Distribution of Remaining Oil by the Composite Index of Heterogeneity

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Abstract. As the Xingbei Development Zone gradually goes into the extra high water cut stage, the difficulty of residual oil tapping is becoming harder and harder. Heterogeneity not only controls the injection agent's sweep coefficient, but also controls the injection displacement efficiency, which is the key factor affecting the formation and distribution of residual oil.

Characterization of reservoir macroscopic heterogeneity by parameters such as sedimentary microfacies, oil layer structure, permeability, porosity and net thickness ratio. The heterogeneous comprehensive index obtained by the wave superposition method can not only quantitatively evaluate reservoir heterogeneity, but also explain the distribution characteristics of the residual oil.

Using this method to fit the eastern part of a district of Xingbei Oilfield, The obtained heterogeneous composite index (I_{RH}) distribution map is compared with the reservoir numerical simulation residual oil saturation map, and the correlation between the two is good. Statistically fit the production of new wells in the simulated area, wells with heterogeneous composite index between 0.55 and 0.75 have higher cumulative oil production, average daily oil production, and the water content is 2-5 percent lower than the average. According to the comprehensive analysis, the remaining oil enrichment area is in the I_{RH} [0.55, 0.75] region. Guided by this method, we report Well B1; let free its S II 8 accompanying water blocking layer, so as to strengthen liquid supply to Well B2 and Well B3, which are rich in residual oil through this method. The production plan proves to be effective, Well B2’s daily oil production increases by 1.5t, and Well B3’s daily oil production increases by 1.2t. Till now, the accumulated increasing oil production has up to 1324t, which equals to economic benefits of 3840,000 RMB.

Through quantitative characterization of reservoir heterogeneity, we find that the remaining oil enrichment zone is mostly located in the I_{RH} [0.55, 0.75] region, which has important guiding significance for the future development.

Keywords: Heterogeneous Composite Index, Wave Superposition, Residual Oil

1. Introduction
As Xingbei development zone gradually enters the stage of ultra-high water cut, the difficulty of tapping the remaining oil potential gradually increases. Reservoir heterogeneity not only controls the sweep efficiency of the injection agent, but also controls the displacement efficiency of the injection agent, which is the key factor that affects the formation and distribution of the remaining oil [1-3]. Scholars at home and abroad have characterized the reservoir heterogeneity from different perspectives. In 1973, Pettijohn classified it into five types, which are scale of strata, scale of sand body, etc. In 1986, Weber classified it into seven types, which are boundary of genetic unit, permeable layer in genetic unit, etc. In 1997, Qiu Yinan classified it into five types, which are pore size, sample size, etc [4]. The heterogeneity of reservoirs in China's oilfields is usually divided into four types: interlaminar, planar, intraformative and microscopic [5]. In 2000, Yang Shaochun, a Chinese scholar, put forward the concept of heterogeneous comprehensive index, which not only can describe the heterogeneity in detail, but also can quantify the qualitative description and predict the relative enrichment area of remaining oil. It has been applied in the relevant research of Bohai Bay Basin and Pearl River Mouth basin with very good effect.

2. Principle of Heterogeneous Composite Index

Macroscopically, the distribution of remaining oil is mainly controlled by sedimentary microfacies, structures, fluid properties and reservoir heterogeneity [6-8]. Specifically, porosity, permeability, sedimentary microfacies, reservoir structure, net to gross thickness ratio and other parameters reflect the macro heterogeneity of the reservoir [9-10]. The comprehensive index of heterogeneity calculated based on these parameters can not only carry out the quantitative evaluation of reservoir heterogeneity, but also reveal the distribution characteristics of remaining oil saturation and remaining oil reserves.

On the basis of compiling the plane distribution map of sedimentary microfacies, the micro structure map of oil layer and the distribution map of porosity, permeability, shale content, oil saturation, effective thickness and other parameters, by giving different weight values, normalizing different parameters, synthesizing and superimposing these maps, the comprehensive index of heterogeneity can be obtained to characterize the heterogeneity of reservoir comprehensively and predict the relative enrichment area of remaining oil quickly and intuitively. In the process of obtaining the comprehensive index of heterogeneity, the principle of wave superposition is adopted, that is, the map reflecting the quality of reservoir and the map reflecting the geometric shape of reservoir are superposed, and the weighted average value is calculated to obtain the comprehensive index of heterogeneity, and then the contour map of the value is compiled. If the composite index of heterogeneity is expressed by $I_{RH}$, then:

$$I_{RH} = \sum_{i=1}^{N} w_i x_i$$

Where $w_i$ in the formula is the weight of parameter $X_i$, $i = 1, 2, ..., N$ is the number of variables, where $n = 5$. In the actual calculation, because the units of the above five parameters are not uniform and the sizes are different greatly, they are first normalized and uniformly demarcated between 0 and 1, 0 represents non reservoir and 1 represents high quality reservoir, and then the heterogeneous composite index ($I_{RH}$) of each well point is calculated by Formula 1, and its distribution range is [0, 1].
3. Establishment of Evaluation Model

3.1 Determination Method of Core Parameters

3.1.1 Net to Gross Thickness Ratio
The ratio of net thickness to gross thickness refers to the ratio of effective thickness of oil layer to sand body thickness. The distribution range of the value is [0, 1], so no special transformation is necessary.

3.1.2 Porosity
Porosity value should be normalized to 0-1. The lower limit value of porosity in a given reservoir is assigned to 0, and the maximum average porosity is assigned to 1. In practice, the range transformation method (formula 4-1) is used to transform and calculate the parameters. The data dimension after range transformation is uniform, the distribution range is [0, 1], and the correlation degree between variables before and after the transformation is unchanged.

3.1.3 Permeability
Due to the wide range of permeability value distribution, the huge difference between the values increases the difficulty of normalization of this parameter.

The results show that the range transformation method can not get the ideal results. After many tests, the permeability values are first calculated as logarithm, and then discounted by logKmin / logKmax, and then the range transformation of the new parameters can get the ideal results.

3.1.4 Sedimentary Microfacies
According to the core analysis and log interpretation results of different microfacies in each well of Putaohua Oilfield, the reservoir space size (V × φ) and permeability (K) of different genetic reservoirs are mainly considered to assign values to each sedimentary microfacies. The results of analysis, test and interpretation show that the porosity and permeability of the main channel reservoir of underwater distributary are the best, so the value of this kind of reservoir is assigned to 1, while that of mudstone is assigned to 0 because it is a non reservoir, and that of other microfacies types is assigned to different values according to the relative differences between the reservoir space, permeability and the main channel microfacies of underwater distributary.
Table 1. Sedimentary Microfacies Assignment Table

| Microfacies                        | Value |
|-----------------------------------|-------|
| Underwater distributary channel   | 1     |
| Main thin sand                    | 0.7   |
| Non main thin sand                | 0.5   |
| Surface sand layer                | 0.2   |
| Pinch out Area                    | 0     |

3.1.5 Structural Characteristics
According to the relationship between the structure of oil layer and the distribution of remaining oil, 0 is taken for the lowest part and 1 is taken for the highest part of the structure of each layer. According to the difference of the structure position, the characteristic values of different structure parts are given by the range transformation method, and the distribution range is [0, 1].

Figure 2. Structural Height Conversion Diagram

3.2 Using AHP to Get the Weight Vector of Evaluation Factors
Combined with the actual situation of the study area, this paper uses AHP to get the weight vector of different control factors. Through this method, the first step is to construct the judgment matrix C, the matrix data is obtained by comparing the evaluation indexes; then the maximum eigenvalue $\lambda$ of the judgment matrix and its corresponding eigenvector $\omega$ (weight coefficient vector) are obtained.

3.2.1 Establishment of Judgment Matrix and Consistency Test
The judgment matrix represents the relative importance of each evaluation factor. In this study, 1, 2, 3 and 4 grades are taken. People's understanding differences and the complexity of objective things determine the existence of incomplete consistency in the judgment matrix. AHP allows the existence of incomplete consistency, but it needs to have general consistency, so it needs to test the consistency of the judgment matrix. To test the consistency of the judgment matrix, the first step is to get the maximum eigenvalue $\lambda$ of the judgment matrix, then to solve the consistency index $CI$ (Formula 2) of the test parameter by $\lambda$, and then to calculate the consistency ratio $CR$ (Formula 3) by $CI$. When $CR < 0.10$, the judgment matrix is considered to pass the consistency test; otherwise, the judgment matrix needs to be adjusted until it passes the consistency test.

$$CI = \frac{\lambda - n}{n - 1}$$  \hspace{1cm} (2)

Note: $\lambda$ is the maximum eigenvalue of the judgment matrix, and n is the order of the judgment matrix.
Note: $RI$ is a random consistency index, as shown in Table 2.

Table 2. Random consistency index

| Order | 1  | 2   | 3    | 4    | 5    | 6    | 7    | 8    |
|-------|----|-----|------|------|------|------|------|------|
| RI    | 0  | 0   | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 |

According to the importance of each control factor, the judgment matrix of the study area is established (Table 3):

Table 3. Judgment Matrix of Study Area

|   | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |
|---|-------|-------|-------|-------|-------|
| $C_1$ | 1     | 1/3   | 2     | 1/4   | 1/4   |
| $C_2$ | 3     | 1     | 2     | 1/4   | 1/4   |
| $C_3$ | 1/2   | 1/2   | 1     | 1/2   | 1/3   |
| $C_4$ | 4     | 4     | 2     | 1     | 1/2   |
| $C_5$ | 4     | 4     | 3     | 2     | 1     |

Note: $C_1$, $C_2$, $C_3$, $C_4$ and $C_5$ respectively represent net to gross thickness ratio, porosity, permeability, sedimentary microfacies and structural height.

Judgment matrix consistency parameter $\lambda = 5.26$, $CI = 0.065$, $RI = 1.12$, $Cr = 0.058 < 0.10$, the consistency test is passed!

3.2.2 Calculation of Weight Vector

The weight vector of the control factor, that is, the normalized row vector of $\lambda$ corresponding to the non-zero eigenvector

$$C\omega = \lambda \omega$$

Note: $C$ is the judgment matrix in Table 3.

The non-zero eigenvector $\omega$ of $\lambda$ is calculated by formula 4, and the weight vector $\sigma = (0.162, 0.147, 0.105, 0.251, 0.335)$ is obtained by normalizing $\omega$, that is, the weight distribution of evaluation factors shown in Table 5.

Table 4. Weight of evaluation factors

| Evaluation Factors | net to gross thickness ratio | porosity | permeability | sedimentary microfacies | structural height |
|--------------------|----------------------------|----------|--------------|-------------------------|------------------|
| Weight Value       | 0.215                      | 0.115    | 0.184        | 0.182                   | 0.1              |

4. Verification of Evaluation Results

Draw the plane distribution of the heterogeneous composite index (IRH), then compare it with the remaining oil saturation map of reservoir numerical simulation, it is found that there is a good correlation between the IRH and the remaining oil saturation map.
According to the statistics of new wells in the east of a certain area, it is found that the cumulative oil production and average daily oil production of wells with heterogeneous composite index between 0.55-0.75 are relatively high, and the water cut is 2-5 percentage points lower. When IRH > 0.75, the reservoir physical properties are better, the degree of water washing is higher, and the remaining oil saturation is lower. When IRH < 0.55, the reservoir physical properties are worse, and the reservoir capacity is lower. The area delineated by 0.55 < IRH < 0.75 is the remaining oil enrichment area.

Table 5. Production Situation of Oil Wells with Different Heterogeneous Comprehensive Index

| Well No. | Average Daily Oil Production (t) | Current Water Cut (%) | Cumulative Oil Production (t) | Composite Index $I_{RH}$ |
|----------|---------------------------------|-----------------------|-------------------------------|--------------------------|
| X1       | 2.47                            | 83.44                 | 6313                          | 0.69                     |
| X2       | 2.04                            | 92.51                 | 4458                          | 0.66                     |
| X3       | 1.30                            | 92.87                 | 3323                          | 0.61                     |
| X4       | 1.41                            | 94.75                 | 3092                          | 0.61                     |
| X5       | 1.26                            | 92.24                 | 3218                          | 0.62                     |
| X6       | 0.98                            | 95.97                 | 2153                          | 0.59                     |
| X7       | 0.85                            | 96.89                 | 2177                          | 0.57                     |
| X8       | 0.71                            | 96.43                 | 1809                          | 0.58                     |
| X9       | 0.28                            | 98.22                 | 708                           | 0.82                     |
| X10      | 0.79                            | 99.08                 | 2011                          | 0.84                     |
5. Application and Benefits
In June 2015, Well B1 in a certain area was rezoned to liberate the S II 8 accompanying shutdown layer.
In order to enhance the liquid supply for well B2 and well B3, which are predicted to be rich in residual oil, the daily oil increase of well B2 and well B3 is 1.5t and 1.2t after the scheme works. Up to now, the cumulative oil increase of well B2 is 1324t and the economic benefit is 3.84 million RMB; The heterogeneous comprehensive index method is used to explain the distribution of remaining oil in 15 layers.
The wells with multi-layer remaining oil enrichment are fractured, and the wells with single-layer remaining oil enrichment are perforations added or the fluid supply enhanced. 11 wells are planned to be fractured, and 5 wells are perforations added. Up to now, the cumulative increase in oil production is 12970t, which is equivalent to 37.61 million RMB of economic benefit.

6. Conclusion
The comprehensive index of heterogeneity has good practicability for the prediction of remaining oil in the river delta reservoir.
In Xingbei Development Zone, the remaining oil of the well with the heterogeneity composite index between 0.55-0.75 is relatively rich and has great development potential. When IRH > 0.75, the reservoir physical properties are better, the degree of water washing is higher, and the saturation of remaining oil is lower. When IRH < 0.55, the reservoir physical properties are worse and the storage capacity is lower.

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