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Evaluation of the Water Flooding Development Potential at High Water Cut Reservoirs with the Multi-Level Fuzzy Synthetic Evaluation Method

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At present, most of China's onshore oil reservoirs are facing big challenges as they have entered the stage of high water content. For high water cut reservoirs, conventional reservoir engineering methods, such as the production decline curve analysis method, the water drive characteristic curve analysis method, the forecasting model method and so on, are away from the actual situation at some degree in predicting the difference of water flooding development potential. And it is hard to meet the requirements in mid-to-late stage of high water cut reservoir development by accurately judging the development potential. This paper, through reservoir response, optimizes the elected geological and development indexes that can reflect the water flooding development potential combining the grey correlation and Delphi methods. Then the multi-level fuzzy synthetic evaluation method was established by combining the analytic hierarchy process and the fuzzy evaluation process considering the geological and development factors, and was applied to objectively evaluate the water flooding development potential. At last, through case study of the Baikouquan Reservoir in the 21st Wellblock, it has been proved that this method is effective and feasible.

1. Introduction

In order to forecast the water flooding development potential, at the beginning of the oilfield development, we often conduct a preliminary judgement of recovery factor and recoverable reserves with the empirical formula method, and during middle and late development, we often use reservoir engineering methods, such as the production decline curve analysis method, water drive characteristic curve analysis method and prediction model method, etc. to predict recoverable reserves and the calibration process (Jiang, 2000; Wu, 2017). For high water cut reservoirs, the traditional reservoir engineering methods considering single factor is not comprehensive, making it difficult to reflect the potential of reservoir water flooding development. Factors impacting water drive development potential can be divided into geological and development ones with complex relation between each other and effects on the assessment objectives (Fu, 2001; Luo, 2005; Wu and Xiao, 2012).

Based on the dynamic response of reservoir, combined with the grey relation and Delphi methods, factors were selected with high correlation with water flooding development potential and those with the most influence, after being taken through the optimized selection, mainly included sixteen factors such as porosity, average pore throat radius, effective permeability, etc. and were further divided into six categories according to its influence section: three kinds of geological factors (pore permeability characteristics, the displacement characteristics and geological mining characteristics) and three kinds of development factors (using characteristics, mining characteristics and water flooding characteristics).

2. Analytic Hierarchy Process

Analytic hierarchy process (AHP) is a systematic hierarchical analysis method combining qualitative and quantitative analysis. It has wide application in military command, transportation, education, medical treatment and other fields. In this paper, the specific application approaches to it are as follows:

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Firstly, a hierarchy model was set up. The factors related to the evaluation target were decomposed into several levels according to a certain attribute relationship. In this paper, the hierarchical structure for the layer of primary-level indicators, usually including a single factor, was composed of evaluation objects; The second layer contained secondary indicators; And the third layer included tertiary indicators.
Secondly, the judgment matrix was constructed. By use of scale 1 to 9 the judgement matrices were constructed respectively regarding the importance of the indexes in the third layer relative to the secondary indexes and of the secondary indexes relative to the primary index.
Finally, the consistency test was conducted against the judgment matrices constructed in the second step. First of all, calculate the maximum characteristic value of the judgment matrix; Secondly, use the consistency index to calculate the consistency ratio of consistency index in the the look-up table and for consistency inspection. If the consistency check is OK, weight distribution is reasonable; Otherwise, there need construct the judgment matrix.

2.1 Construction of Evaluation Index System for Water Flooding Potential

The evaluation index system for water flooding potential in high water cut reservoir was built based on the optimized geological and development factors and the multistage evaluation indexes including both the secondary indexes and tertiary indexes. (See Table 1).

Table 1: The potential evaluation index system for the water flooding development

The first level indicators	The secondary level indicators	The third level indicators
A Water flooding development potential	A_1 Poroperm characteristics	A_{11} Porosity A_{12} Average pore throat radius A_{13} Effective permeability
	A_2 Displacement characteristics	A_{21} Original oil saturation A_{22} Residual oil saturation A_{23} Water displacement efficiency
	A_3 Geological mining characteristics	A_{31} Shale content A_{32} Formation oil/water viscosity ratio A_{33} Formation water salinity
	A_4 Using characteristics	A_{41} Water drive reserves control degree A_{42} Water flooding reserves producing level
	A_5 Development characteristics	A_{51} Comprehensive water cut A_{52} Production speed A_{53} Recovery degree
	A_6 Waterflooding characteristics	A_{61} Water cut rising rate A_{62} Percentage points to note

2.2 The Determination of Assessment Index System

After the evaluation index system was built, there need construct a judgment matrix. The analytic hierarchy process (AHP) was used to construct the judgement matrix based on the evaluation objects for comparison between two important objects, and degree of relative importance, scale 1 to 9, was assigned to them with this method.
The reference table in Table 2 shows the judgment matrix of relative importance between the third-level indicators and the secondary indicators as well as that between the secondary indicators and the primary index respectively.

Table 2: Reference table of matrix judgement scale

The importance of scale (x_i, x_j)	Comparison
1	Comparing x_i and y_i, they have same importance
3	Comparing x_i and y_i, the first one has a little more importance
5	Comparing x_i and y_i, the first one has more importance
7	Comparing x_i and y_i, the first one has much more importance
9	Comparing x_i and y_i, the first one has much more strong importance
2 4 6 8	Degree between adjacent judgment above

And then the weight vector will be calculated with the root product method and column inversion method as major methods. In this article the column inversion method has been used with the specific calculation process as follows:

Set a_{ij} as the judgment matrix, and the importance scale refers to the relative importance of the indicator j to the i indicator. The calculation steps are as follows:

1. Set up m judgment matrix as below:

$$A = \begin{bmatrix} a_{11} & a_{21} & \cdots & a_{m1} \\ a_{21} & a_{22} & \cdots & a_{m2} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix} \tag{1}$$

2. Normalize the judgment matrix of each column with below normalization formula:

$$b_{ij} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \tag{2}$$

3. Add the matrix obtained from formula (2) and obtain below formula:

$$b_i = \sum_{j=1}^{n} b_{ij} \tag{3}$$

4. Normalize the column for $b_i=(b_1, b_2, \ldots, b_n)^T$ according to below normalization formula:

$$u_k^{(j)} = \frac{b_k}{\sum_{i=1}^{n} b_i} \tag{4}$$

The result $u_k^{(j)} = (u_1^{(j)}, u_2^{(j)}, \ldots, u_n^{(j)})^T$ is the weight vector of the secondary index j, $u^{(i)} = (u^{(1)}, u^{(2)}, \ldots, u^{m})^T$ is the weight vector of the secondary indexes relative to the primary index, also we can have the third weight vector $u_k^{(j)}$.

5. Calculate the comprehensive weights as below:

Table 3: Evaluation index weights

Evaluation index		Weight	Consistency check
A	A_1	0.19	λ=6.07
	A_2	0.36	RI=1.2492
	A_3	0.10	CR=0.01
	A_4	0.16	
	A_5	0.12	
	A_6	0.07	
A_1	A_{11}	0.20	λ=3.05
	A_{12}	0.31	RI=0.5149
	A_{13}	0.49	CR=0.05
A_2	A_{21}	0.25	λ=3
	A_{22}	0.25	RI=0.5149
	A_{23}	0.50	CR=0
A_3	A_{31}	0.16	λ=3.01
	A_{32}	0.54	RI=0
	A_{33}	0.30	CR=0.01
A_4	A_{41}	0.50	λ=2 RI=0
	A_{42}	0.50	CR=0
A_5	A_{51}	0.54	λ=3.01
	A_{52}	0.16	RI=0
	A_{53}	0.30	CR=0.01
A_6	A_{61}	0.60	λ=2
	A_{62}	0.40	RI=0
	A_{63}	0.50	CR=0

$$u = u_k^{(j)} \times u^{(j)} \tag{5}$$

By formula (6) consistency of judgment matrix constructed can be obtained:

$$CR = \frac{\lambda - n}{(n-1)RI} \tag{6}$$

In the equation (6), λ determines the maximum eigenvalue of matrix, n is the number of evaluation objects, and RI is the mean random consistency index, which is usually in the look-up table. In general, if the consistency ratio CR≤0.1, we regard the judgment matrix passes the consistency check, otherwise, there need construct the judgment matrix. Weight calculation results are as shown in Table 3.

3. Fuzzy Evaluation Method

Fuzzy comprehensive evaluation method is a kind of comprehensive evaluation method based on fuzzy mathematics, and it is a membership to describe fuzzy boundaries. Therefore, on the basis of fuzzy geometry, fuzzy comprehensive evaluation method conducts comprehensive analysis of the membership grade for various indexes of evaluation objects. On the one hand, the hierarchy of study objects can reflect the multilevel fuzzy evaluation results; On the other hand, the results will be clearly systemic so that it can better solve the problems hard to quantify through quantitative research based on membership degree principle (Tang et al., 2002; Sun, 2008; Tang et al., 2001; Gao et al., 2003, Jiang, 2014).

The results of fuzzy comprehensive evaluation method are not absolutely yes or no, but fuzzy sets. This article constructed a three-level evaluation body requiring primary and secondary, as well as secondary and tertiary evaluation indexes, and the specific calculation steps are as following:

1. Determine the evaluation factor set:

$$A = \{A_1, A_2, \cdots, A_i\} \tag{7}$$

In which, A_i is the index in the index system; i is the index serial number.

2. Determine the evaluation set and assignment:

$$V = \{V_1, V_2, \ldots, V_m\} \tag{8}$$

$$P = [P_1, P_2, \ldots, P_m] \tag{9}$$

Where V is the collection that contains evaluation of different ranks; P stands for the assignment for the corresponding evaluation grades.

3. Determine the weight vector of indexes at all levels

$$U = [U_1, U_2, \ldots, U_i] \tag{10}$$

Where U is the index weight vector.

4. Determine the evaluation matrix

$$R = [B_1, B_2, B_3, B_4, B_5, B_6]^T \tag{11}$$

5. Make the fuzzy comprehensive evaluation

The weight vector of the evaluation index and the formula in step 4 constitute a fuzzy synthetic evaluation matrix transformation with below comprehensive evaluation result:

$$B = U \times R \tag{12}$$

According to the fuzzy evaluation set $B_i = B_{i1}, B_{i2}, \ldots, B_{im}$, B_{in} is the evaluation set of indicator i , V_i is the membership of fuzzy comprehensive evaluation set B_i. According to the principle of maximum membership degree, the corresponding fuzzy comprehensive evaluation results M_i is:

$$M_i = \max(B_{i1}, B_{i2}, \cdots, B_{in}) \tag{13}$$

4. Case Study

The 21st Wellblock of the Baikouquan Oilfield has been exploited since 1979. Based on the early 500m spacing synchronous water-flooding development mode, it has later been encrypted to 9 points from the five point well pattern to the space of 300-350 m. Through the production decline and water drive curve analysis methods, the recoverable reserves are still small with poor water flooding development potential. However, no matter from the actual dynamic reflection or expert assessment, the reservoir owns good potential of water flooding development.

Based on data in this paper, the multistage fuzzy comprehensive evaluation method was used to evaluate the water flooding development potential of the the Baikouquan Cut Reservoir in the 21st Wellblock. The required geologic and development parameters were collected and checked as listed in Table 4.

Table 4: Evaluation indexes of Baikouquan formation in Bai 21 block

Index, Unit	Number
A_{11} Porosity %	12.2
A_{12} Average pore throat radius μm	7
A_{13} Effective permeability 10^{-3} μm	71.2
A_{21} Original oil saturation %	60
A_{22} Residual oil saturation %	31
A_{23} Water displacement efficiency %	48.5
A_{31} Shale content %	5
A_{32} Formation oil/water viscosity ratio /	5
A_{33} Formation water salinity mg/L	6250
A_{41}Water drive reserves control degree %	89.2
A_{42} Water flooding reserves producing level %	43.5
A_{51}Comprehensive water cut %	89.5
A_{52} Production speed %	0.23
A_{53} Recovery degree %	27.8
A_{61} Water cut rising rate %	1.6

The multistage fuzzy comprehensive evaluation method mentioned in this paper was used to evaluate the instance block, and comprehensive evaluation results are as shown in Table 5.

Table 5: Evaluation result of water flooding development potential

Water flooding development potential fuzzy evaluation set		Evaluation Result
B_1	[0.304,0.496,0.000,0.199,0.001]	Better
B_2	[0.000,0.250,0.747,0.002,0.000]	Medium
B_3	[0.562,0.317,0.121,0.000,0.000]	Best
B_4	[0.000,0.409,0.091,0.000,0.500]	Better
B_5	[0.540,0.019,0.340,0.049,0.052]	Best
B_6	[0.496,0.121,0.144,0.146,0.093]	Best
B	[0.214,0.292,0.347,0.055,0.093]	Medium

It can be seen from the final evaluation results that in the the Baikouquan Cut Reservoir of the 21st Wellblock, most secondary indexes are at good level except the displacement characteristics of the secondary level that caused the overall evaluation results to be of medium level, the conclusion of poor potential is superior to the reservoir engineering method. From the research results of this paper, it is preliminarily thought that the main factor influencing the water flooding development potential is the displacement characteristics of the reservoir.

Based on the evaluation results, this paper presents the development proposal (He et al., 2012) that the 21st Wellblock of the Baikouquan Cut Reservoir should further explore its water flooding potential based on its current fine water flooding, and further study the synchronization of primary, secondary and tertiary recovery in reservoir adaptability research and the timing of the tertiary oil recovery so as to further improve the reservoir recovery factor and its long-term sustainable development .

5. Conclusion

In terms of high water cut reservoir, as the reservoir engineering method often can't reflect the potential of water flooding development, this paper selects geological and development factors with the grey correlation method combined with the Delphi method so as to establish an evaluation system of the water drive development potential at high water cut reservoirs for multi-level fuzzy comprehensive evaluation in combination of chromatography analysis and fuzzy evaluation methods. Evaluating the the Baikouquan Reservoir in the 21st Wellblock, its water flooding development potential was tested to be at the medium level, which is in line with the actual development dynamic, confirming that this method, being effective and feasible, is of a certain guiding significance and reference to the water flooding development of other middle- and high-water cut reservoirs.

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