Study and application on the evaluation method of porous formation for long-term waterflooding sand reservoir

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Abstract: Nine targets which stand both for the static characteristic of produced formations and the dynamic parameter of wells including the average permeability, variation coefficient of permeability, moving capability, remaining recoverable reserves, coefficient of flooding, daily oil production, increasing rate of water cut, cumulative liquid production per unit meter and efficiency index of oil production are selected as the evaluation indexes, a novel model to evaluate the porous formations in long-term waterflooding sand reservoir was established by using the support vector machine and clustering analysis. Data of 57 wells from Shentuo 21 block Shengli oilfield was analyzed by using the model. Four kinds of formation groups were gained. According to the analysis result, different adjustment solutions were put forward to develop the relevant formations. The Monthly oil production increased 7.6 % and the water cut decreased 8.9 % after the adjusted solutions. Good results indicate that the learning from this method gained will be valuable adding to other long-term waterflooding sand reservoirs in Shengli oilfield and other similar reservoirs worldwide.

Key words: long-term waterflooding reservoir; support vector machine; clustering; formation evaluation; adjustment solution

1 Introduction

Differences of the oil recovery among different produced formations of long-term waterflooding sand reservoir which lead to poor effect for the initial design development project. Finding technical schemes to develop this kind of reservoir effectively proves to be one of the key problems for reservoir developers[1]. However, how to find effective solutions to solve this dilemma becomes a key problem for every reservoir developer. In fact, although the oil recovery of some porous formations is high due to long-term waterflooding action, there are still parts of formations which have not been swept and contain fairly high reserves[2]. Therefore, the oil production rate can be enhanced if these formations are selected to be the aim for development, and it also is one of the effective solutions for developing this kind of reservoirs. On the other hand, it is a complex task to evaluate all the produced porous formations because of their high uncertainty. Support vector machine (SVM) technique is a useful method based on statistics learning theory[3]. It can obtain an optimal network structure by learning limited sample data and the precision is good enough for engineering requirement[4]. These characteristic make it more useful for intelligent analysis in engineering field. Clustering algorithm is an important instrument for recognizing statistical pattern, it can classify samples into different groups according to their interval margin by using mathematical technique[5]. A novel method is proposed to evaluate the produced porous formations by using SVM and the clustering algorithm in the paper.

2 Theoretical bases

2.1 SVM classify algorithm

Suppose samples x_i belong to class y_i, (x_i, y_i), $x \in R^d$, $y_i \in \{+1, -1\}$, $i = 1,2,3,\cdots n$, d is a positive integer. The optimal problem of classifying samples correctly by using the optimal separating hyperplane equation $w \cdot x + b = 0$ and obtaining a maximal margin can be described as:

Seek the minimum of variable $\varphi(\boldsymbol{w}) = \frac{1}{2}\|\boldsymbol{w}\|^2 = \frac{1}{2}(\boldsymbol{w} \cdot \boldsymbol{w})$ under the constraint equation $y_i[(\boldsymbol{w} \cdot x_i) + b] - 1 \geqslant 0, i = 1,2,3,\cdots,n$. In order to solve the question, usually we transform it into its dual problem[6]. Its dual equation is under the constraint equation $\sum_{i=1}^{n} y_i\alpha_i = 0$ and $\alpha_i \geqslant 0, i = 1,2,3,...n$, seeking the maximum solution of the following equation.

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$$Q(\alpha) = \sum_{i=1}^{n} \alpha_i - \frac{1}{2}\alpha_i\alpha_j y_i y_j (x_i \cdot x_j) \quad (1)$$

When seek the optimal value (α_i^* , w^* , b^*) from coefficients of α_i, w, b, the optimal classified function is

$$f(x) = \mathrm{sgn}[(w^* \cdot x) + b^*] = \mathrm{sgn}\left[\sum_{i=1}^{n} \alpha_i^* y_i (x_i \cdot x) + b^*\right] \quad (2)$$

At the same time, the objective function of searching optimal solution can be described as

$$Q(\alpha) = \sum_{i=1}^{n} \alpha_i - \frac{1}{2}\sum_{i,j=1}^{n} \alpha_i\alpha_j y_i y_j k(x_i \cdot x_j) \quad (3)$$

Accordingly the classified function can be described as

$$f(x) = \mathrm{sgn}\left[\sum_{i=1}^{n} \alpha_i^* y_i k(x_i \cdot x) + b^*\right] \quad (4)$$

When the problem is transformed into its dual ones, both of the objective function of searching optimal solution and the classified function are only involved in calculating its inner product among the training samples ($x_i \cdot x_j$) . The calculation work can be finished by using the kernel function in the original space. According to the functional theory, if one kernel function $K(x_i, x_j)$ can meet the qualification of Mercer, it equals to make corresponding interior product in a certain transformed space[7]. Therefore, by selecting optimal kernel function of interior product in optimal separating hyper-plane, the mapping from low to high dimensional space can be obtained. As a result, the nonlinear classified algorithm can be transformed into its linear one while the calculation complexity has not been increased. The kernel function can transform a nonlinear calculation in high dimensional space into a linear calculation of kernel function in original space, therefore, it can avoid Curse-of-Dimensionality[8]. Four kinds of kernel functions are the linear kernel function, the polynomial kernel function, the radial radix kernel function and the sigmoid kernel function[9].

2.2 Clustering algorithm

Clustering algorithm can be used to sort different kinds of data which are collected according to their format, size and front. Modes of the data which in common use are pattern vectors, pattern matrix and similarity matrix. Similarity matrix is a $P \times P$ matrix, its row and line are on behalf of pattern and the elements of the matrix are on behalf of the approximate degree between the corresponding pair of patterns. The pattern matrix is a $P \times P$ matrix composed of vectors; its row is on behalf of pattern and line is character. All the N characters can be looked as a group of vertical intersecting axis.

A clustering genus is assembled of such points in pattern space, the margin between two points in an aggregation cluster is small than the margin between a random point in it and other random point out the cluster. In order to classify the pattern aggregation correctly, an analogical measurement is needed to measure the comparability among the same kind of samples and the differences among other samples. The four measurements in common use are O-margin, Ma-margin, the common Ming-margin and the similar function of angle[9].

The O-margin is adopted as the comparability measurement. According to margin calculated from different sets of matrix composed of nine indexes of different porous formations and the cluster center, the formation can be decided to which cluster it belongs.

As for two samples $\boldsymbol{x} = (x_1, x_2 \cdots x_n)^T$, $\boldsymbol{z} = (z_1, z_2, \cdots, z_n)^T$,

The O-margin can be defined as

$$D = \sqrt{(x_1 - z_1)^2 + \cdots + (x_n - z_n)^2} \quad (5)$$

3 Evaluation model of porous formation

3.1 Select targets for porous formation evaluation

Nine targets which stand both for the static characteristic of produced formations and the dynamic parameter of wells are selected as the evaluation indexes. a. Average permeability (K), permeability is an index which indicates fluid ability of the porous media[10]. Average permeability is the average value of the formation permeability, mD. b. Variation coefficient of permeability (V), ratio of the mean square deviation and the average value of permeability, its value indicates the level of heterogeneity in the same formation[11]. $V = \sqrt{\sum_{i=1}^{n} (K_i - \bar{K})^2 / n} \Big/ \bar{K}$, dimensionless. c. Moving capability (F), it means the vertical moving capability of the formation. $F = K_l h_l / H\bar{K}$, dimensionless. d. Remaining recoverable reserves (R). It indicates the potential of the oil-bearing formation. $R = (S_o - S_{or}) A_l h_l \phi_l$ [12], $10^4 m^3$. e. Coefficient of flooding (W), thickness ratio of flooding and total formation. $W = H' / H$ [13], dimensionless. f. Daily oil production (P), m^3/d. g. Increasing rate of water cut (C), it indicates the increasing speed of the water cut. $C = (W_{C2} - W_{C1}) / (F_{oe2} - F_{oe1})$, dimensionless. h. Cumulative liquid production per unit meter (L), the cumulative liquid production per unit meter of the porous formation, $10^4 m^3$/m. i. Efficiency index of oil production (E), ratio of cumulative oil production and water cut of the porous formation, $10^4 m^3$.

K_i —Permeability of formation i; $\bar{K}$ —Average permeability of formation; n—Number of formations;

$\Phi_l h_l$ —Porosity & thickness of formation l; H—Thickness of total formation; $K_l h_l$ —Permeability & thickness of formation l; H—Thickness of flooding; S_o, S_{or}— Oil & residual oil saturation; A_l, h_l —Area & thickness of formation l; W_{C2}, W_{C1} —Water cut of final & initial stage; F_{oe2}, F_{oe1}—Recovery percent of reserves of final & initial stage.

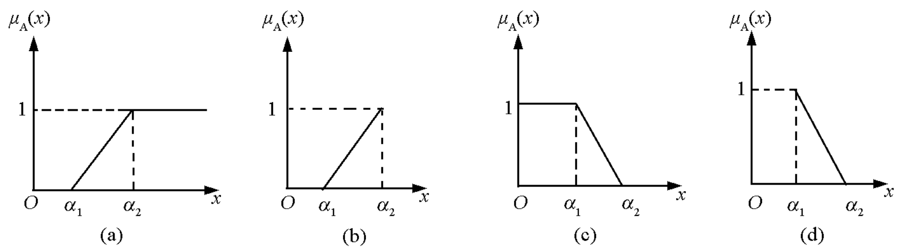
3.2 Data processing

According to the principle of relative optimization, the targets are divided into two groups, one group is the larger value, the better option (A) and the other is the smaller value, the better option (B)[14,15]. The trapezoid distribution shown in Fig. 1 is adopted to describe the characteristic of targets. Analysis indicates that targets included average permeability, moving capability, remaining recoverable reserves, coefficient of flooding, daily oil production, cumulative liquid production per unit meter and efficiency index of oil production belong to group A, the other targets belong to group B. Ascending trapezoid distribution is used to describe the targets in group A and descending ones to describe the targets in group B. Mathematical model of the ascending trapezoid and descending trapezoid distribution which are shown in Fig. 1(a) and Fig. 1(b) are given by

$$\mu_A(x) = \frac{x-\alpha_1}{\alpha_2-\alpha_1} \qquad \alpha_1 \leqslant x \leqslant \alpha_2,$$

$$\mu_A(x) = \frac{\alpha_2-x}{\alpha_2-\alpha_1} \qquad \alpha_1 \leqslant x \leqslant \alpha_2 \tag{6}$$

Where α_1 and α_2 are the minimum and the maximum value of a single target.



(a)—Ascending half trapezoid; (b)—Simplified ascending half trapezoid;
(c)—Descending half trapezoid; (d)—Simplified descending half trapezoid

Fig. 1 Curve of trapezoid distribution

3.3 Evaluation model of the porous formation

Firstly nine major factors which probably have influence on evaluation are regarded as the input parameters of the model, the classification machine can choose the optimal kernel function and interior parameters by learning the classified sample data, all these contents make up of the interior network of the model for the reservoir. Data can be classified correctly by using this model; also the margin between sample and the hyper-plane can be calculated. Secondly, the format of clustering items has been set in a matrix $(K,V,F,R,W,P,C,L,E,M)^{\mathrm{T}}$ according to the clustering theory. Thirdly, after setting the comparability measurement (O-margin) and threshold, all the samples can be decided to which classifications they belong according to the fact whether the value of their O-margins are included in the threshold level set before.

The principle of clustering algorithm of porous formations evaluation can be described as

Firstly, suppose n groups of data of produced formations: $X_1, \cdots, X_n$, any one group at random is set as a clustering center Z_1, a reasonable nonnegative value T_0 is set as threshold, and $X_1 = Z_1$. O-margin D_{21} from X_2 to Z_1 is then calculated. If $D_{21} > T_0$, Z_2 will be set as a new clustering center, otherwise X_2 belongs to center Z_1 and X_1, X_2 belong to the same classification. Secondly, calculate D_{31} and D_{32} which are margins from the third group data X_3 to the first and second clustering center Z_1 and Z_2. If $D_{31} > T_0$ and $D_{32} > T_0$, Z_3 will be regarded as a new clustering center and $X_3 = Z_3$, otherwise X_3 will be classified into its nearer clustering center. At last, C_1 groups of classifications, C_1 clustering centers and the number of samples in each classification will be gained after finishing calculating all the produced formation data to the end.

4 Result discussions and application

Analysis data is acquired from Shengtuo 21 block Shengli oilfield[16], parts of the training samples are listed in Table 1. Radial radix kernel function is proved to be the best kernel function after comparing its result error with others. The minimal predicted error is 3.78 % which included in the permission of engineering precision[17]. The comparison result is shown in Fig. 2. Data of 57 wells from Shentuo 21 block was analyzed by using the model. Four kinds of formation groups were gained. Results are shown in Table 2 and Fig. 3.

Table 1 Parts of the training samples

No.	Static factors					Dynamic factors				y
	K	V	F	R	W	P	C	L	E	
1	0.75	0.37	0.77	0.78	0.68	0.76	0.68	0.24	0.64	+1
2	0.54	0.68	0.31	0.64	0.59	0.46	0.19	0.59	0.57	-1
3	0.66	0.45	0.46	0.37	0.71	0.93	0.79	0.17	0.43	+1
4	0.65	0.33	0.66	0.80	0.29	0.65	0.56	0.49	0.72	+1
5	0.71	0.19	0.83	0.69	0.35	1.00	0.78	0.88	0.78	+1
6	0.28	0.86	0.49	0.47	0.44	0.24	0.43	0.29	0.35	-1

Table 2 Evaluation results for T21 reservoir

Groups	Major characteristic	Porous formations
A	High for residual oil and moving capability	1^{1}, 1^{3}, 2^{5-2}, 3^{4}, 7^{3}, 7^{4}, 8^{2-2}, 9^{1-1}, 9^{1-2}
B	High for oil production and efficiency of oil production	2^{4}, 8^{1-1}, 8^{1-2}, 8^{3-1}, 8^{3-3}, 10^{1}, 10^{2}
C	Low for formation energy and increasing rate of water cut	1^{2}, 2^{5-1}, 3^{5}, 6^{5}, 8^{1-3}, 8^{2-1}
D	Invalid circulate for injection	8^{3-2}, 9^{1-3}

According to the analysis result, four adjustment solutions are put forward to develop the four groups of formations. Owing to the higher residual oil, moving capability and efficiency of oil production in the formation of group A and B, the recommended Countermeasure is increasing the injection and production rate. Due to low formation energy of group C, the recommended Countermeasure is increasing the injection rate while decreasing the production rate. Because of invalid circulate for injection of group D, we suggest shut these formations. The Monthly oil production increased 7.6 % and the water cut decreased 8.9 % (Fig. 4 & Fig. 5) after the adjusted solutions.

5 Conclusions

1) A novel model was established by using SVM and clustering theory to evaluate the long-term produced porous formation. Nine selected targets which stand both for the static characteristic of produced formations and the dynamic parameter of wells including the average permeability, variation coefficient of permeability, moving capability, remaining recoverable reserves, coefficient of flooding, daily oil production, increasing rate of water cut, cumulative liquid production per unit meter and efficiency index of oil production are reasonable for evaluating targets of porous formation.

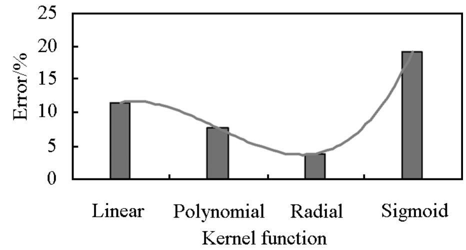


Fig. 2 Predicted errors of different kernel functions

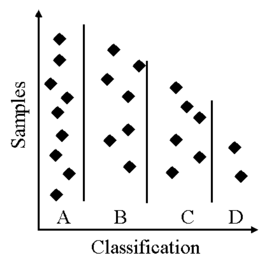


Fig. 3 Analysis results

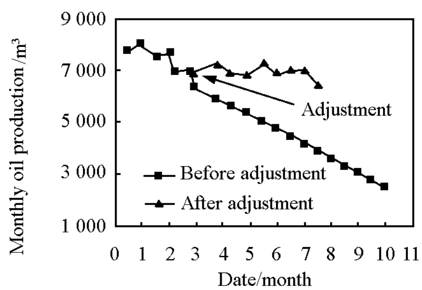


Fig. 4 Monthly oil production of the block before & after adjustment

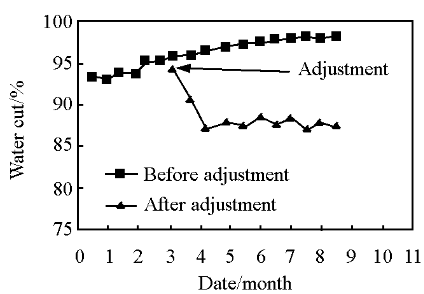


Fig. 5 Water cut of the block before & after adjustment

2) Data of 57 wells from Shentuo 21 block Shengli oilfield was analyzed by using the model. Four kinds of formation groups were gained. According to the analysis result, different adjustment solutions were put forward to develop the relevant formations. The Monthly oil production increased 7.6 % and the water cut decreased 8.9 % after the adjusted solutions.

3) Good results indicate that the learning from this method gained will be valuable adding to other long-term waterflooding sand reservoirs in Shengli oilfield and other similar reservoirs worldwide.

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