Establishment and Application of Sand Prediction Model Based on Monte Carlo Method in Offshore Oil-gas Field

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Abstract. Accurate assessment of reservoir sanding risk is a key link in the optimization design of offshore oil-gas fields. Based on the Monte Carlo risk probability assessment method, three factors affecting sand production, such as rock Poisson's ratio, rock density and acoustic time difference, are considered. At the same time, combined with the existing sand production index prediction theory, the probability distribution calculation model of sand risk is established and analyzed. The established prediction model is used to analyze the sand production case. The model was combined with the logging data and seismic data of some layers in Oilfield HZ 32-5 to form the probability distribution map of the sand production index of the J22, J50 and K08 horizons in HZ 32-5 Oilfield. The probability of different sand production levels of the three reservoir rock horizons is predicted, and the corresponding sand control risk prevention and control plan is formulated. Through the on-site application of HZ 32-5 Oilfield, it is proved that the model can more accurately assess the sand production risk in offshore oilfields, and has a good guiding significance for the design of oil-gas well completion schemes.

1. Introduction

China, as a power rich in marine oil-gas resources, has great potential for exploration and development. While complex geological environment of most offshore oil-gas fields plus with construction factors will cause the formation to easily have the sand production, resulting in wearing ground casing and inducing accidents, and the production will be impaired in severe situation [1,2,3]. Whereas, the development of offshore oil-gas fields is featured with expensive investment, high risk and rigid technical requirements when compared to onshore oil-gas fields, the sand production in offshore oil-gas fields may cause greater potential damage and economic loss. Hence, they have become key links to evaluate the risk of sand production prior to the design of the well completion plan, provide theoretical basis for selection of well completion method, select the sand control strategy, and conduct the risk assessment and analysis on sand production in the development of offshore oil-gas field.

There are various traditional methods for sand production prediction, including the on-site observation method, empirical prediction method, experimental prediction and theoretical model prediction method [4-7]. The sand prediction on the site can be quickly made with the on-site observation method. The seismic well logging data, petrophysical parameters and field experience are used in the empirical prediction method to predict the formation. The experimental prediction method is used to take prediction by simulating the sand production experiment close to actual situation of the well. The theoretical model prediction is the prediction model set up based on the fluid-solid coupling model of the formation or constitutive model of rock mechanics. The sand production index in the
empirical prediction in this paper serves as the basic theory. Monte Carlo calculation method is used to calculate the risk probability of the sand production index, analyse the probabilities of different sand production degrees, and formulate appropriate sand risk prevention and control plan. The sand production risk prediction and management for some reservoirs of HZ 32-5 Oilfield are explored through established prediction model in combination with logging data and seismic data of the horizon to guide the design of well completion program.

2. Analysis on Sand Production Mechanism and Influencing Factors

The conditions of sand production in oil-gas production wells varies, and the situations shown are different, whereas they remain their own characteristics and are roughly divided into four types, namely the shear failure mechanism, tensile failure mechanism, and particle migration mechanism. And sand arch stabilizing sand production mechanism [8,9]. Excessively high or low production pressure difference makes the formation fluid flow / unstable and the rock is subject to the tensile action. The constant change of reservoir pressure or water content leads to high-speed flow of the sand discharge fluid, affecting the formation pressure, all these factors aggravates the degree of sand production of the production well. Therefore, the intersection rock mechanics and multiple disciplines must be involved and support each other in the study of sand production.

There are numerous influencing factors in the sand production of oil-gas wells, including physical factors of reservoir locations and engineering factors [10,11,12]. The physical factors cover the rock strength, cementing materials in rocks, reservoir pressure, formation stress. The engineering factors cover the essentials of production pressure difference, oil production rate, stimulation measures.

3. Assessment Model for Sand Production Risk

Traditional analytical and laboratory sand prediction analysis techniques are based on known crude oil well parameters and physicochemical properties of reservoir (located in different regions and depths), and the sand productions are determined by the field evaluation, test and laboratory experiments. The data available near the formation is normally used to infer relevant properties of distant places and deep blocks due to the lack of physical data in the field or formation rock. These methods are only used for deterministic analysis with the objective of determining the production pressure differential for sand production near the bottom of the well or near the well bottom. These methods have been established and are widely used, and nevertheless they rely heavily on the accuracy of field data. Therefore, their application may only be limited to the sand production analysis on classical rock mechanics instead of satisfaction of the requirements of on-site drilling and completion operations.

3.1. Prediction Methods for Traditional Sand Production

3.1.1. Acoustic Time Difference Method. The propagation time difference of acoustic waves in this method in the formation to determine the sand production, the acoustic time difference is the reciprocal of propagation velocity of the longitudinal wave along the well profile, which is recorded as $\Delta t_c = \frac{1}{c}$. The greater the time difference of acoustic wave of formation is, the higher the porosity of the formation is, indicating that the looser the formation is, and it is easier to generate the sand production. The acoustic wave time difference $\Delta t_c$ is used to determine the sand production of the oil well. The time difference value of acoustic wave varies with different oil fields and blocks. The oil well is easy to produce the sand during normal production under normal circumstances when $\Delta t_c \geq 295 \mu s / m$ is satisfied.

3.1.2. Combined Modulus Method. The combined modulus method is an empirical method of Mobil, and the density, a sensitive parameter of sandstone reservoir based on the acoustic time difference method is led in this method, the elastic modulus $E_\gamma$ of rock determined by the acoustic time difference and rock density is used to determine of the reservoir is subject to the sand production. The elastic modulus $E_\gamma$ of the rock is to be calculated with the following formula:
\[ E_t = \frac{9.94 \times 10^8 \rho_r}{\Delta t^2} \]  

(1)

Where: \( E_t \) denotes the combined elastic modulus MPa of the rock; \( \rho_r \) represents the density of the formation rock or g/cm\(^3\); \( \Delta t \) denotes the acoustic time difference of longitudinal wave of the rock.

3.1.3. Sand Production Index. The sand production index is also called the sand production index or the one-way Young's modulus, and sand production degree of different horizons and formations can be determined according to the size of the sand production index. When this index is used to determine if the formation is subject to the sand production, firstly, the logging curves including the acoustic time difference and density logging are digitally treated and then the rock strength parameters of different parts are gotten, and the sand production index of different production sections of the oil well is calculated. The calculation formula is:

\[ B_s = \frac{E}{3(1-2\nu)} + \frac{4\rho_r}{3\Delta t^2} \]  

(2)

Where: \( B_s \) denotes the sand production index (MPa); \( E \) denotes Young's modulus of rock (10\(^4\)MPa); \( \nu \) denotes the Poisson's ratio of rock (dimensionless); and \( \Delta t \) denotes horizontal acoustic time difference of the rock (\( \mu s / ft \)).

3.1.4. Schlumberger Method. Schlumberger method is proposed by Schlumberger. The well logging is made according to mechanical properties, and the shear modulus of rock in the formation and the compressibility of rock volume are gotten. When the value of Schlumberger is great, it indicates that the rock is of high strength and good stability and is not prone to be subject to the sand production; otherwise, it is prone to be subject to the sand production. The calculation formula is shown as follows:

\[ \frac{G}{C_s} = \frac{(9.94 \times 10^8)^2}{6(1-\nu)^2(1+\nu)^2\rho_r^2 \Delta t^2} \]  

(3)

Where: \( C_s \) denotes the rock volume compression coefficient (1 / MPa).

The on-site application of Schlumberger shows that the oil well is not subject to the sand production \( G/C_s > 3.8 \times 10^7 \) MPa is true; and the oil well is subject to the sand production when \( G/C_s < 3.8 \times 10^7 \) MPa is true.

3.2. Introduction to Simulation Method of Monte Carlo

The Monte Carlo method, based on the principle of mathematical statistics, is also known as the stochastic simulation method, and it is a unique numerical method not developed with the development of electronic computer [12,13]. It is known from the probability that the probability of some event may be estimated by the occurrence frequency of that event in a large number of experiments, and the occurrence frequency of such event may be considered as its probability when the sample size is large enough. Therefore, substantial random may be firstly applied on random variables affecting their reliability, and then these sample values are substituted into the functional function group to determine if the structure is invalid, and finally the failure probability of the structure is obtained. The Monte Carlo method is analyzed based on that idea.

Statistically independent random variables \( x_i(i=1,2,3,\ldots,k) \) are set, whose corresponding probability density functions are \( f_{x_1}, f_{x_2},\ldots,f_{x_k} \), and the functional function is \( Z = g(x_1, x_2, \ldots, x_k) \).

Firstly, according to the corresponding distribution of random variables, N sets of random numbers \( x_1, x_2, \ldots, x_k \) values are generated, and the functional function value \( Z = g(x_1, x_2, \ldots, x_k) \) is calculated (\( i = 1, 2, \ldots, N \)). If there is a functional function value \( Z \leq 0 \) corresponding to the L sets of random numbers, then the characteristics according to Bernoulli’s large number theorem and the normal random variable include the structural failure probability and reliable index when \( N \rightarrow \infty \) is true.
It can be seen from the idea of Monte Carlo method that the method avoids the mathematical difficulty in structural reliability analysis, while an accurate failure probability and reliability indicators comparison may be gotten as long as the number of simulation is sufficient regardless of nonlinear availability of state function and non-normal availability of the random variable or not.

4. Field Application

4.1. Basic Data of Examples
The oil reservoir of HZ 32-5 Oilfield is distributed in the Zhujiang Formation of Neogene and Zhuhai Formation of Paleogene, it belongs to the middle-low medium-deep reservoir in terms of buried depth, and it is vertically and upwardly divided into 9 reservoirs, of which 4 bottom water reservoirs (J-22B, J-50, K-22 and M-10), 5 edge water reservoirs (J-22A, K-08, K-15B, L-10 and L-60) are included. The reservoir lithology is dominated with the sandstone and sandstone interbed. The relevant parameters of each reservoir are shown in Table 1.

Table 1. Physical properties of oil reservoir in Oilfield HZ32-5 and temperature and pressure system

| Oilfield | J22 | J50 | K08 |
|----------|-----|-----|-----|
| Horizon  |     |     |     |
| Porosity, % | 15.3~25.9 | 19.3~24.3 | 16.4~27.4 |
| Permeability, mD | 124.6~1628.7 | 480.3~1384.7 | 105~3069.5 |
| Initial formation pressure, MPa | 16.6 | 17.7 | 18.5 |
| Formation temperature, °C | 83 | 89 | 90.5 |
| Saturation pressure of crude oil, MPa | 0.95 | 3.76 | 6.42 |
| Solution gas-oil ratio, m³/m³ | 5 | 50 | 48 |
| Crude oil density of formation, g/cm³ | 0.775 | 0.736 | 0.739 |
| Crude oil viscosity of formation, mPa•s | 1.28~2.57 |
| Crude oil density of ground, g/cm³ | 0.819 | 0.811 | 0.825 |
| Crude oil viscosity of ground, mPa•s | 2.74 | 1.78 | 3.27 |

4.2. Sand Production Calculation of Monte Carlo
The sand production risk assessment in this paper is based on the Monte Carlo method in combination with the sand production index calculation formula (2). In consideration of the independence requirement between random variables and the collectability of data, the formation rock density, Poisson's ratio of rock and longitudinal wave time difference are selected as random variables. The formation rock density, Poisson's ratio of rock and longitudinal wave time difference in the model are random variables with certain range of values.

Firstly, the data including the stratum density, Poisson's ratio of rock and longitudinally acoustic time difference are collected and eliminated, and the singular points are eliminated. Then, Monte Carlo simulation software is used to establish the probability distribution curves for parameters. When the parameters are few, the actual probability distribution curve may be constructed according to the distribution profile of the parameter (e.g normal distribution, lognormal distribution model, etc.). The results such as Figure 1, the parts of (a),(b),(c) shown for the probability distribution curve of rock density, Poisson ratio and longitudinal acoustic wave time difference of Stratum J22 of HZ 32-5 Oilfield. Secondly, according to the probability distribution curve for parameters, the empirical distribution function of each parameter is constructed, the random number is generated by computer, the random value serves as the probability entrance value, and the rock density value corresponding to the probability is obtained by the interpolation method in empirical distribution function for rock density, and another random value is used to get the time difference of longitudinal acoustic wave of
corresponding rock stratum based on the difference distribution function for longitudinal acoustic wave time. The values of parameters taken in Rock Stratum J22 of Oilfield 32-5 in Huizhou are obtained according to Formula (2), and thousands of sand production index values are obtained, then the results are statistically analyzed to get the probability distribution curve for rock sand production index value of J22 Rock Stratum of 32-5 Oilfield in Huizhou in figure 1d.

![Probability distribution diagram for rock density in Formation J22](image1)

![Probability distribution diagram for Poisson ratio in Formation J22](image2)

![Probability distribution diagram for longitudinally acoustic time difference in Formation J22](image3)

![Probability distribution diagram for sand production index with Monte Carlo method in Formation J22](image4)

Figure 1. Application results of Monte Carlo method in Formation J22

![Probability distribution diagram for rock density in Formation J50](image5)

![Probability distribution diagram for Poisson ratio in Formation J50](image6)
According to the figures through from Figure 1 to Figure 3, the sand production index values of Monte Carlo of Rock Stratum J22, Rock Stratum J50 and Rock Stratum K08 of HZ 32-5 Oilfield are calculated, and the summary table for distribution probabilities of sand production under different sand production index values is summarized (Table 2).
Table 2. Sand production probability under different sand production indexes (MPa)

| Stratum | Sand production index value <14000 | 14000< Sand production index value <20000 | Sand production index value >20000 |
|---------|-----------------------------------|---------------------------------|---------------------------------|
| J22     | 2.58%                             | 9.75%                           | 87.67%                          |
| J50     | 31.27%                            | 14.38%                          | 54.35%                          |
| K08     | 76.34%                            | 20.89%                          | 2.77%                           |

It can be concluded from the above table that the sand production index of Reservoir J22 of HZ 32-5 Oilfield is greater than 20000 MPa, and its maximum probability hits 87.67%, being determined to be slight sand production of reservoir; the sand production index of Reservoir J50 is greater than 20000 MPa, and its maximum probability hits 54.34%, while the probability sand production index value less than 14000 MPa is also relatively high, and its probability is 31.27%, being determined to be the sand production of reservoir; the sand index of Reservoir K08 is less than 14000 MPa, and its maximum probability hits 76.34%, being determined to be serious sand production of in reservoir.

It is suggested that the development of Reservoir J22 of HZ 32-5 Oilfield may be equipped with simple sand control completion, the development of Reservoir J50 is to be applied with the sieve completion method, and the development of K08 reservoir is to be applied with layered gravel filling & completion method for Reservoir K08.

5. Conclusion and Recommendation
(1) A Monte Carlo-based sand risk assessment model shall be established to make full use of the strata and development data of developed wells around the oil-gas fields and to get the probability distribution curve for the sand production by simulation calculation and statistics. Existing data is greatly utilized in this way, and the results are closer to the real situation.
(2) The model is capable of deriving the probabilities of different sand production levels, effectively quantifying various sanding risk values, and conducting the risk assessment in better manner.
(3) The model is applied to the prediction of sand production in oil-gas wells with similar oil reservoir and completion methods, the impacts of different completion methods on sand production risk are not considered, and further research may be conducted.

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