Research and Application of Wellbore Stability Based on Quantitative Risk Analysis

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Abstract. The weakly consolidated sands of Guantao Formation in Bohai has shallow buried depth, low degree of compaction and frequent wellbore collapse. The research on wellbore stability is very important for the efficient development of this kind of low resistivity reservoir. This study involves many parameters, including rock modulus, rock strength, in-situ stress and other parameters. And the uncertainty of these parameters is difficult to avoid. Traditional methods usually ignore the influence of the uncertainty of model parameters on the fracture pressure and collapse pressure, and the prediction results are often difficult to meet the field operation requirements. Based on the constitutive equation and failure criterion of rock deformation, a classical wellbore stability model is established. Using data from core experiments, field tests, and logging evaluations, the mean, maximum, and minimum values of the model input parameters are statistically obtained. And the sensitivity analysis of the model parameters is carried out to identify the key parameters of the model. According to the probability density function (PDF) of the model parameters, Monte Carlo simulation technology is used for random sampling. Then tens of thousands of random sampling results are substituted into the wellbore stability model to calculate the probability density functions (PDFs) of fracture pressure and collapse pressure. Sensitivity analyses show that maximum horizontal stress, internal friction angle, cohesion and Poisson's ratio are the major variables to determine collapse pressure. And maximum and minimum horizontal stresses, Poisson's ratio are the most critical parameters in fracture pressure evaluation. Finally, an uncertainty analysis is presented in the form of probabilistic graphs. The safe mud density window is obtained as a probability function of the risk of borehole instability. This provides a reasonable range of drilling fluid density for field operators. When the reliability of input parameters is high, any value in the interval of [P50, P90] is selected as the prediction result. When the uncertainty of input parameters is high, P90 is used as the prediction result. In this paper, Monte Carlo simulation is used to quantify the uncertainty of each input parameter, and the risk of borehole collapse and leakage is quantitatively expressed in the form of probability. It can provide reliable reference for drilling fluid density design and reduce the risk of drilling operation.

Keywords: Weakly consolidated sands · Wellbore stability · Uncertainty · Monte Carlo simulation · Drilling fluid density

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1 Introduction

Wellbore instability is one of the main problems in the efficient development of low resistivity reservoirs in Guantao Formation, Bohai Oilfield. Borehole collapse, drilling fluid leakage and other problems related to wellbore stability have become one of the main causes for low efficiency of drilling. And it causes huge economic losses and operation challenges [1]. In order to solve the problem of wellbore instability, many research methods have been put forward, including elastic model, elastic-plastic model, porous elastic model, mechanical chemical coupling model, etc. [2–5]. These studies are all based on the deterministic research methods. In fact, due to the lack of data, measurement tool errors and other factors, the parameters related to wellbore stability research, such as rock modulus, rock strength, in-situ stress, have a certain degree of uncertainty. Because the classical model ignores the influence of the uncertainty of input parameters, the model results will inevitably produce large errors, and even lead to wrong prediction conclusions. Therefore, based on the classic wellbore stability model, the PDFs of the input parameters of the model are established by using statistical method. Then, the Monte Carlo simulation technology is used to randomly sample the input parameters, and the influence of the uncertainty of the input parameters on the model results is quantitatively evaluated. And the cumulative probability distribution function of the safe drilling fluid density window is obtained. It could provide suggestions for field drilling operation.

2 Wellbore Stability Model

2.1 Mechanism of Wellbore Instability

Before drilling, under the combined action of overburden pressure, maximum and minimum horizontal stresses and pore pressure, the underground rock is in a state of stress balance. After drilling, the rock is brought to the ground in the form of cuttings, which breaks the stress balance near the borehole. The hydrostatic pressure of drilling fluid becomes a new stress support for the rock near the wellbore. Drilling results in redistribution of stress around the hole, which causes stress concentration on the borehole wall. Whether the borehole is unstable or not depends on the drilling fluid density. When the mud density is too low, the radial stress decreases and the tangential stress increase on the borehole. For brittle rock, the shear failure occurs at the maximum shear stress point, which leads to the collapse and block falling of the rock on the wellbore. For plastic rock, the plastic flow leads to the reduction of diameter, which is easy to cause drilling jam. When the mud density is too high, the tangential stress becomes tensile stress. When it exceeds the tensile strength, tensile fracture occurs on the wellbore, resulting in drilling fluid leakage [6].

2.2 Construction of Wellbore Stability Model

The key of wellbore stability research is to evaluate the degree of borehole stress concentration caused by drilling. The stress distribution around the wellbore is the basis of wellbore stability modeling. It depends on the far-field in-situ stresses, reservoir pore pressure and hydrostatic pressure of mud [7]. The form of stress around the wellbore are as follows:

$$\sigma_r = P_i - \delta\phi\left(P_i - P_p\right) \tag{1}$$

$$\sigma_\theta = -P_i + (\sigma_H + \sigma_h) - 2(\sigma_H - \sigma_h)\cos 2\theta + \delta\left(\alpha\frac{1-2\nu}{1-\nu} - \phi\right)\left(P_i - P_p\right) \tag{2}$$

$$\sigma_z = \sigma_V - 2\nu(\sigma_H - \sigma_h)\cos 2\theta + \delta\left(\alpha\frac{1-2\nu}{1-\nu} - \phi\right)\left(P_i - P_p\right) \tag{3}$$

where, σ_r, σ_θ, σ_z are the radial, tangential and axial stresses, respectively, P_i is the hydrostatic pressure of mud, P_p is the reservoir pore pressure, σ_V is the overburden pressure, σ_H, σ_h are the maximum and minimum horizontal stress, respectively, θ is the angle between the target element and the positive direction of x-axis, ν is Poisson's ration, α is Biot coefficient, δ is the permeability coefficient of borehole, ϕ is porosity. Due to the small depth and good physical properties of the target interval, it could be assumed $P_i = P_p$.

When the tangential stress is greater than the tensile strength(St), tensile failure occurs on the borehole. When $\theta = 0^\circ$ or 180°, the effective tangential stress reaches the minimum. Then, the fracture pressure is given by:

$$P_{if} = 3\sigma_h - \sigma_H + S_t - \alpha P_p \tag{4}$$

According to the Mohr & Coulomb theory, when $\theta = 0^\circ$ or 180°, the difference between the effective circumferential stress and the effective radial stress on the wellbore reaches the maximum, and the shear failure occurs. Then, the collapse pressure is given by:

$$P_{ic} = \frac{3\sigma_H - \sigma_h - 2KC_0 + \alpha P_p(K^2 - 1)}{K^2 + 1} \tag{5}$$

where, C_0 is the cohesion, φ is the internal friction angle, K equals $\tan(45^\circ + \varphi/2)$.

Finally, the safe density window of drilling fluid is obtained

$$\rho_{max} = \frac{P_{if}}{TVD} \times 100 \tag{6}$$

$$\rho_{min} = \frac{P_{ic}}{TVD} \times 100 \tag{7}$$

3 Quantitative Risk Analysis of Wellbore Stability

Once finishing the modeling of wellbore stability, the influence of the uncertainty of the input parameters on the model results could be quantitatively evaluated. After the statistics of the mean, maximum and minimum values, a sensitivity analysis of the model parameters is carried out to determine the key factors. Then the Monte Carlo simulation is used to randomly sample these key parameters, and the sampling results are substituted into the model to calculate the cumulative probability distribution function of the fracture pressure and collapse pressure equivalent density. Finally, quantitative risk analysis (QRA) of wellbore stability is realized.

3.1 Sensitivity Analysis of Model Parameters

Sensitivity analysis is an important tool for quantitative risk assessment. It could identify the key parameters by comparing the influence of these input parameters on the calculation results of the model. Combined with uncertainty analysis, this method will significantly improve the reliability of prediction results of wellbore stability model [8]. As one of the simplest and most commonly used methods, the technique once at a time (OAT method) provides a simple and efficient way of sensitivity analysis. OAT method only changes one variable at a time to investigate the influence of the change of a single variable on the output of the model. The specific procedure is as follows:

(1) According to the data of core experiment, field test and well log, the mean, maximum and minimum values of input parameters are counted;
(2) For a specific parameter, the wellbore stability model is run every time the value of this parameter is changed under the condition that other parameters are equal to the average value, until the whole variation range of this parameter is traversed. Then the calculation results of the model are obtained. The process is repeated for each parameter.
(3) All the parameters are ordered according to their sensitivity, and the key parameters of the model are identified.

Through sensitivity analysis, it is possible to determine the critical parameters that have the greatest impact on wellbore stability, and we need to focus on the accuracy improvement of these parameters. The variables with less influence can be regarded as constants in the uncertainty analysis to reduce the computational time.

Finally, response surface method [9, 10] is also used to analyze the sensitivity of the input parameters, and the reliability of OAT method is verified by parallel comparison.

3.2 Quantitative Risk Analysis

The study of wellbore stability based on deterministic method often provides the specific values of collapse pressure and fracture pressure. However, due to the calculation error of the input parameters and various uncertain factors in field operation, it is sometimes difficult to obtain a safe and complete borehole by using the deterministic method. In order to quantitatively evaluate the instability risk, the uncertainty of input parameters is quantified and transmitted to the model results by Monte Carlo simulation. The probability function of the safe mud weight window on the risk of instability is obtained, which provides a reasonable range of mud weight for field drilling engineers. This procedure can be divided in five stages. And a schematic example of the process is illustrated in Fig. 1.

(1) Based on sensitivity analysis, the PDF of each key parameter is determined according to the minimum, maximum and average values. The commonly used PDFs include normal, lognormal and uniform distributions. The difference between the former two lies in whether the maximum and minimum values are symmetrical with respect to the average value. The PDF of all parameters must satisfy that 99% of the possible values lie between the minimum and maximum values.
(2) According to the PDF of each parameter, the Monte Carlo simulation is used to sample it randomly, from which a value is obtained.
(3) The input parameters obtained in the previous step are used to calculate the model output.
(4) After repeating steps 2 to 4 for N times, the PDFs for collapse and fracture mud weights are generated.
(5) By accumulating the PDF in step 4, the cumulative probability distribution function (CDF) of safe mud weight window is obtained. And it is shown in the final graph in Fig. 1.

In the CDF diagram, the x axis is the reasonable drilling fluid density to avoid instability problems (both collapse and fracture), and the y-axis is the probability of avoiding such problems. The green curve represents the line of mud weights required to avoid borehole collapse, while the light blue curve represents the line of mud weights required to prevent fracturing and circulation losses. The area between the two curves represents the stable zone to drill with respective probabilities. The horizontal line illustrates the range of mud weights that will simultaneously provide at least 80% certainty of avoiding both collapse and lost circulation. This procedure makes it possible to show the proper mud weights in a simple graph in a probabilistic way.

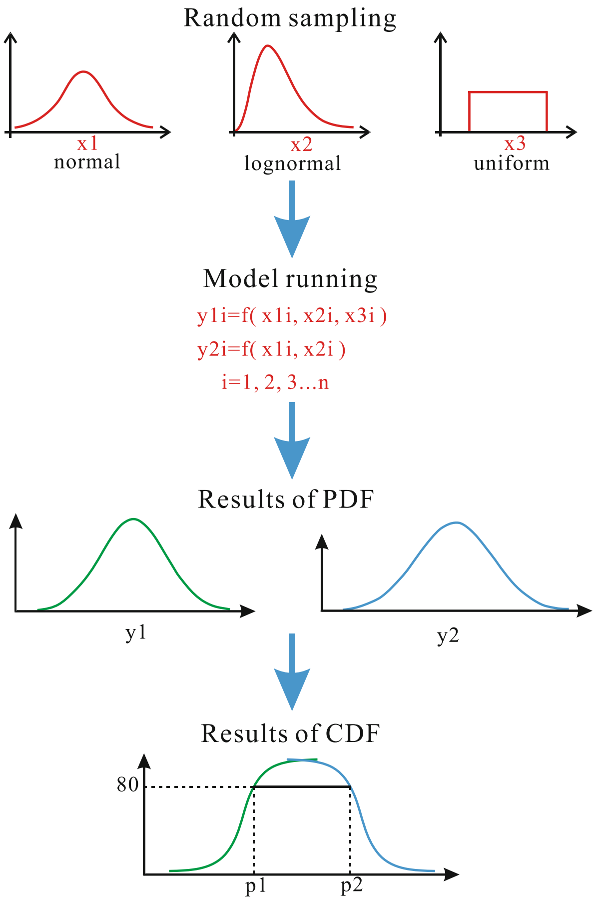


Fig. 1. Diagram of quantitative risk analysis

4 Application

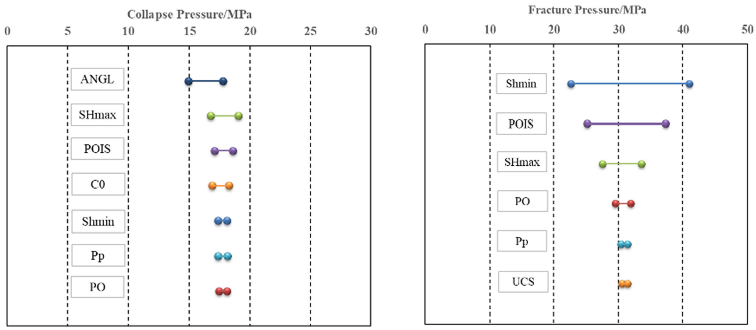
The methodology described was applied to well A8 in Bohai Bay. Deterministic method and QRA are used to evaluate the safe drilling fluid density window, and the differences between the two are compared.

On the basis of core experiment and field test data calibration in the study area, the density and acoustic logging data of well A8 are used to calculate rock mechanics parameters, rock strength and in-situ stress. Table 1 shows the minimum, average and maximum values of these parameters.

Table 1. Input parameters of wellbore stability model

Parameter	Minimum value	Average value	Maximum value
Poisson's ratio /v/v	0.274	0.356	0.433
Overburden Pressure /MPa	28.553	29.716	30.873
Minimum horizontal stress /MPa	21.937	24.646	28.056
Maximum horizontal stress /MPa	26.778	29.509	32.952
Pore pressure /MPa	13.51	14.032	14.554
Uniaxial compressive strength /MPa	1.612	4.843	11.102
Cohesion /MPa	0.329	1.066	2.414
Internal friction angle /°	28.533	48.753	68.484

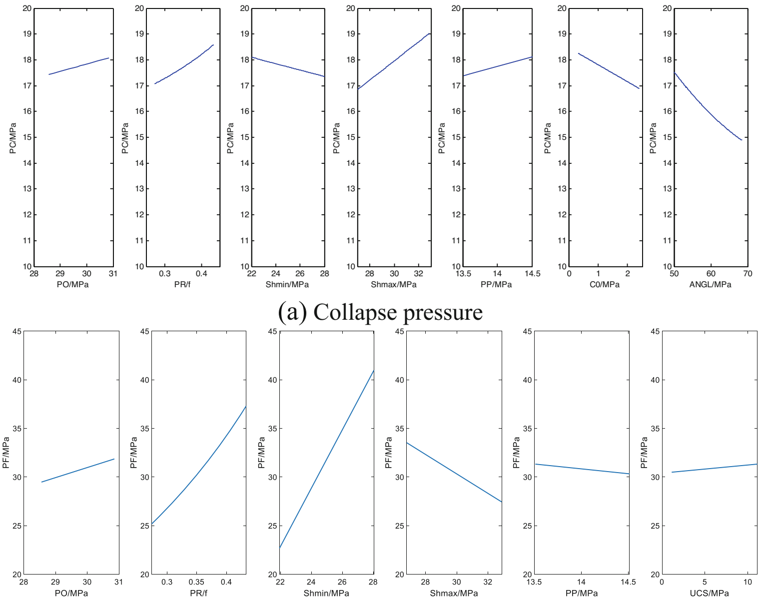
Figure 2 shows the sensitivity analysis of the input parameters by OAT method. In Fig. 2(a), internal friction angle, maximum horizontal stress, Poisson's ratio and cohesion have the greatest effect on the collapse pressure, while the minimum horizontal stress, pore pressure and overburden pressure have little influence. Figure 2(b) shows that minimum horizontal stress, Poisson's ratio and maximum horizontal stress are the key factors to determine the fracture pressure, and overburden pressure, pore pressure and uniaxial compressive strength are the secondary factors.



(a) Collapse pressure (b) Fracture pressure

Fig. 2. Sensitivity analysis based on OAT

Figure 3 shows the sensitivity analysis of the input parameters by response surface method. Figure 3(a) shows the relationship between collapse pressure and input parameters. And the slopes of the curves satisfy the relation: internal friction angle > maximum horizontal stress > Poisson's ratio > cohesion > minimum horizontal stress > pore pressure > overburden pressure. Figure 3(b) shows the relationship between fracture pressure and input parameters. And the slopes of the curves satisfy the relation: minimum horizontal stress > Poisson's ratio > maximum horizontal stress > overburden pressure > pore pressure > uniaxial compressive strength. The higher the slope, the greater the sensitivity of the parameter. Therefore, the analysis results of response surface method and OAT are consistent, and it indicates that the sensitivity analysis results are reliable.

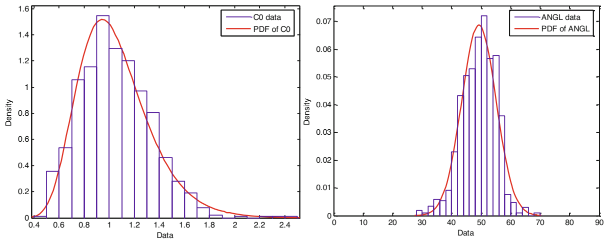


(a) Collapse pressure

(b) Fracture pressure

Fig. 3. Sensitivity analysis based on response surface method

According to the statistical data and sensitivity analysis results, the PDFs of the input parameters are determined. Cohesion obeys lognormal distribution, and other key parameters satisfy normal distribution. Figure 4 shows the PDFs of cohesion and internal friction angle.



(a) Cohesion (b) Internal friction angle

Fig. 4. The PDFs of cohesion and internal friction angle

Figure 5 shows the interpretation results of wellbore stability of well A8 based on deterministic method. At the current depth interval, the mud weight used in the field is 1.1 g/cc (MW in the 11th track). The equivalent mud weight window is calculated by using the classical wellbore stability model (the 10th track). Theoretically, when the actual mud weight is less than the equivalent mud weight of collapse pressure, borehole collapse and expansion will occur. Results of the deterministic method are consistent with the well diameter curve (CAL) in some well sections (red shadow in the 11th track). Because the deterministic method ignores the uncertainty of the input parameters, results of some layers are quite different from the actual data:

(1) At 1350.0–1355.0 m, the actual mud weight is less than the equivalent weight of collapse pressure, but the borehole is still good. And it indicates that the result of the deterministic method in this interval is conservative.
(2) At 1404.0–1412.0 m, although the actual mud weight is greater than the equivalent weight of collapse pressure, serious borehole expansion still occurs. And it indicates that the result of the deterministic method in this section is optimistic.

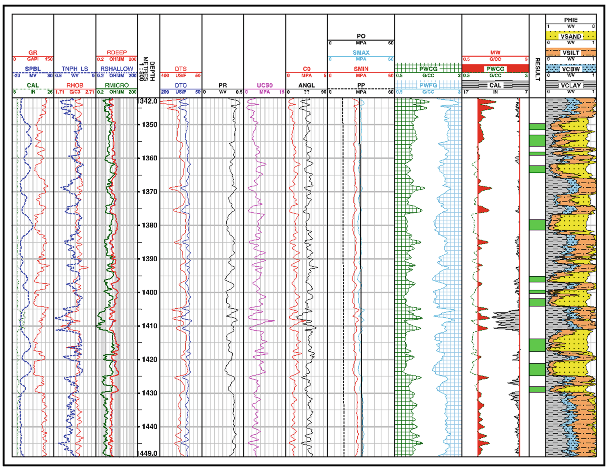
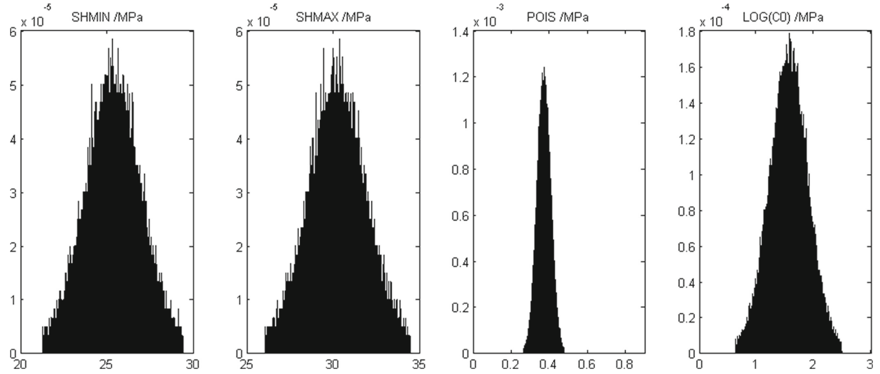
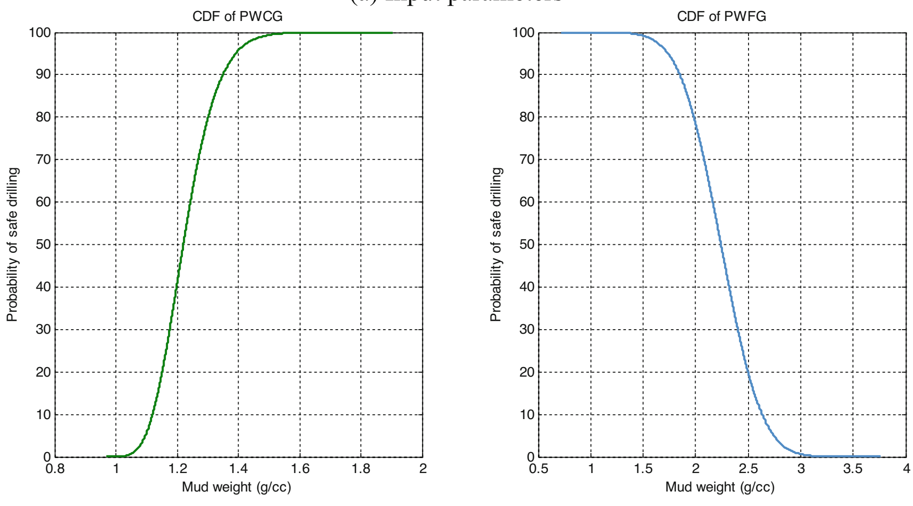


Fig. 5. The interpretation results of wellbore stability of well A8

To compare the difference between the new method and the deterministic method, the wellbore stability based on QRA is carried out for the interval with the most serious borehole enlargement in well A8. Figure 6 shows the results of QRA for 1409.0 m. According to the process shown in Fig. 1, Monte Carlo simulation is used to randomly sample the key input parameters and generate tens of thousands of random values (see Fig. 6(a)). By substituting the random data into the classical wellbore stability model, the CDFs of collapse and fracture equivalent weight are obtained (see Fig. 6(b)).



(a) Input parameters



(b) CFDs of pwcg and pwfg

Fig. 6. Results of wellbore stability based on QRA at 1409.0 m

As the drilling engineers in the study area are mainly faced with the problems of borehole collapse and expansion, only the uncertainty of collapse pressure is analyzed. The analysis method of fracture pressure is consistent with collapse pressure. According to the PDF of equivalent weight of collapse pressure (green curve in Fig. 6 (b)), the analysis yields probabilities of success (no stuck pipe) of 50% and 90% for drilling fluid densities of 1.21 g/cc and 1.35 g/cc, respectively. The result from the classical deterministic analysis suggests that a drilling fluid density of 0.96 g/cc will be required to successfully drill this well. Although the actual mud weight is greater than that from deterministic analysis, serious borehole collapse still occurs. At 1405.0 m–1411.0 m, the density log is greatly affected by borehole collapse, so there is a large uncertainty in the input parameters. For example, the maximum and minimum horizontal stresses are 30 ± 4 MPa, 25 ± 4 MPa. In this case, P90 (the probability of safe drilling is 90%) is selected as the QRA result.

5 Conclusions

(1) Monte Carlo simulation technology fully considers the uncertainty of each parameter, and propagates it to the calculation results through the classical wellbore stability model, which significantly improves the prediction accuracy.
(2) The wellbore stability research based on quantitative risk analysis can quantitatively exhibit the risk of borehole collapse and leakage in the form of probability. And it provides more reliable reference for drilling fluid density design.
(3) The new method provides an effective means for quantitative evaluation of drilling operation risk in the efficient development of weakly consolidated sands oilfields.

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