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A new quantitative evaluation method for drilling risk based on uncertainty analysis

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Abstract

With drilling operations extending to offshore or deep and complex formations, drilling risk is becoming more and more serious. Traditional methods cannot assure the safety of high-risk drilling operations. Therefore, establishing a quantitative evaluation method for drilling risk is becoming increasingly more urgent. In this paper, the credibility of formation pressure and equivalent circulation density (ECD) of drilling fluid were first analyzed based on the Monte Carlo simulation method. Thereafter, the probability distributions of formation pressure and ECD were obtained. Then, based on the generalized stress and strength interference theory, the quantitative method for evaluating drilling risk was established. In this method, the risk factor was defined as the generalized stress (ECD). The safety factor was defined as the generalized intensity (formation pressure). The safety barrier function was defined as the function of drilling risk. In two case studies, this method was used to predict drilling risk probabilities, and the prediction results were in favorable agreement with the actual drilling risk.

Keywords: ECD with credibility; formation pressure with credibility; generalized stress and strength interference theory; Monte-Carlo simulation method.

1. Introduction

Oil and gas drilling engineering involves high investment and high risk, particularly when drilling in deep and complex formations or in offshore formations (Hempkins *et al*., 1987; Ahmed *et al*., 1993; Bratton *et al*., 2001; Gandelman *et al*., 2009). There are a lot of complex and uncertain factors in oil and gas drilling engineering. Due to the complexity of geological environment, the incompleteness of the logging or seismic data, the precision of the mathematical model and other issues, the true value of formation pressure can be difficult to obtain. (Higgins 1993; Lerche, 2012; Wessling *et al*.,2014). Formation pressure constitutes the basic data set for casing program design. The uncertainties or errors regarding formation pressure can result in unreasonable casing program design, which is one of the main causes of drilling risks. The prediction of drilling risk is an essential approach to ensure safe and effective drilling. Numerous researchers have conducted long-term studies on the prediction and evaluation of drilling risk and constructed some classical methods. The main methods include hierarchical analysis, fault tree analysis, profiling of formation pressure with credibility, and artificial neural network methods (Sadiq *et al*., 2004; Khakzad *et al*., 2013; Skogdalen *et al*., 2012; Liu *et al*., 2013; Irani *et al*., 2011). By investigating the existing drilling risk assessment methods, we noted that these traditional methods often neglect the mechanisms of drilling risk. Furthermore, these methods only transplant common risk assessment methods, commonly used in other engineering areas, to drilling engineering. These common methods only provide qualitative or semi-quantitative risk assessments and cannot assure the safety of high-risk drilling. Therefore, a quantitative drilling risk assessment method is required.

2. The method of calculation

2.1 Uncertainty analysis of formation pressure

The uncertainty of formation pressure can lead to unreasonable casing program design, which increases drilling risks. To resolve this problem, a method for establishing formation pressure with credibility was proposed (Ke *et al*., 2009; Sheng *et al*., 2016). The formation pressure predicted by this method was no longer a single numerical value but an interval containing a degree of reliability. This method is practical for drilling engineers as it clarifies their understanding of information regarding formation pressure. The flowchart for calculating the formation pressure with credibility is depicted in Figure 1.

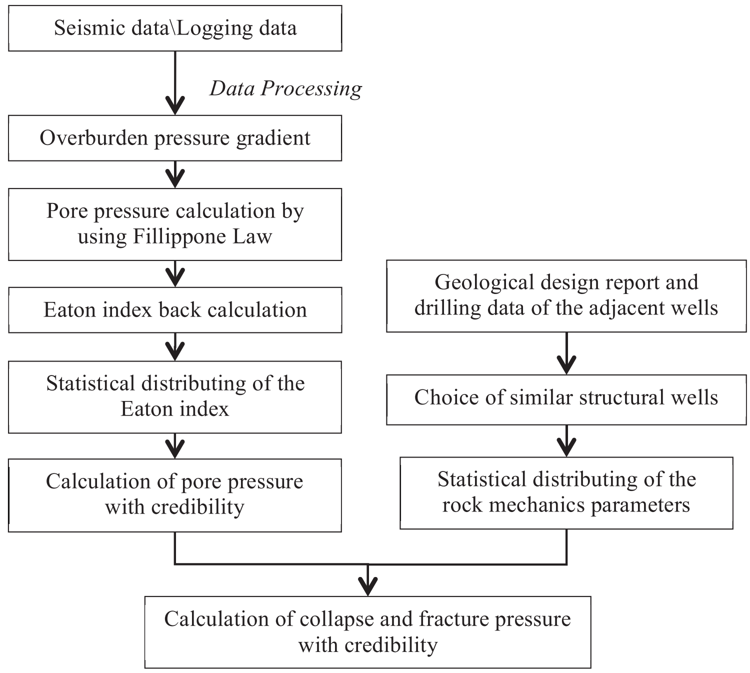

Fig. 1. Flowchart for calculating formation pressure with credibility

2.2 Uncertainty analysis of ECD

The equivalent circulation density (ECD) of drilling fluid is defined as the sum of its equivalent static density (ESD) and the annular pressure loss, given by the following formula:

$$ECD = ESD + \frac{p_c}{gH} \qquad (1)$$

Where, p_c is the annular pressure loss, MPa, and H is the well depth in kilometers.

Many calculation models of ESD and annular pressure loss have been reported (Subramanian *et al*., 2000; Von *et al*., 2004; Reitsma *et al*., 2009; Mokhtari *et al*., 2012; Peng *et al*., 2013). For the sake of brevity, these are not covered in this article. The uncertainty of ECD can increase drilling risk (Mostafavi *et al*., 2011). Therefore, this research puts forth the Monte Carlo simulation to determine its probability distributions. This is a numerical method which returns approximate solutions to engineering problems. It uses random numbers to perform sampling experiments or random simulations. Through the statistics of random variables, the statistical characteristic value is obtained as the numerical solution of the problem.

The termsare $x_1, x_2, \ldots, x_n$ defined as the n direct measurement parameters in the ECD calculation model. **Y** (ECD) stands for a vector of indirect measurement parameters. The function relating the direct and indirect measurement parameters is $Y = F(x_1, x_2, \cdots, x_n)$.

The calculation steps of ECD with credibility are as follows:

Step 1. Determine the probability distribution function of the direct measurement parameters $f_1(x), f_2(x), \ldots, f_n(x)$.

Step 2. According to the requirements of precision, determine the simulation $X_1, X_2, \ldots, X_N$ time. N random number samples are generated in accordance with the characteristics of the probability distribution of the direct parameters: $X_i = [x_{1i}, x_{2i}, \ldots, x_{ni}], (1 < i < N)$.

Step 3. Substitute N random number samples into the formula $Y = F(x_1, x_2, \ldots, x_n)$ to obtain $Y = [Y_1, Y_2, \ldots, Y_N]$.

Step 4. Determine probability distribution function of $Y = [Y_1, Y_2, \ldots, Y_N]$ by employing the normal information diffusion method.

2.3 Quantitative evaluation method for drilling risk

Uncertainty is the main cause of risk. Various authorities have suggested different approaches to resolve engineering safety problems caused by uncertainty in drilling engineering. In drilling engineering design, the safety factor method is currently the most commonly used (Austin *et al*., 1983). However, it requires a deterministic model to express uncertainty, and it is heavily subjective, thus making it theoretically incomplete.

The theory of reliability can evaluate the engineering safety of drilling operations by probabilistic methods (Warren *et al*., 1968). The uncertain factors in engineering are treated as random variables with probability distributions. The various forms of damage that may occur in a project are considered as a system. The degree of safety of the project is then evaluated by using the failure probability of the system. Reliability analysis can provide information by which decision makers can guide the engineering design or operation, so as to improve the safety and reliability of the project.

The generalized stress and strength interference theory was the basic theory of risk evaluation for drilling engineering in this research. In this theory (Sundararajan *et al*., 1995; Huang *et al*., 2009), the factors leading to system failure are defined as generalized stress. Factors that prevent the system failure are defined as generalized strength. The function that relates generalized stress and generalized strength is defined as the safety barrier function. The reliability or failure probability of a system can be determined by analyzing the safety barrier function. In this method, generalized stress is defined as the risk factor (ECD). Generalized intensity is defined as the safety factor (formation pressure). The safety barrier function is defined as the risk function of drilling. Considering well kick risk as an example, the quantitative evaluation method for drilling risk can be described in detail. The function of the drilling fluid is to maintain the bottom hole pressure balance. When the ECD is larger than the pore pressure, the well kick does not occur. Reliability (R) is the probability that the function of the drilling fluid does not fail, given by the following formula:

$$R = P(Q > S) = P(Q - S > 0) = P(Q / S > 1) \tag{2}$$

Where Q denotes the random variables of the ECD of the drilling fluid, and S denotes the random variables of pore pressure. If the drilling fluid satisfies Eq. (2), it can maintain the wellbore pressure balance; otherwise, the function of the drilling fluid fails, leading to a well kick.

As shown in Figure 2, the ECD and pore pressure are both probability distributions. When the two probability distributions interfere with each other, drilling risks may occur. The shaded part indicates the probability of drilling engineering risk. The probability of drilling engineering risk is defined as follows:

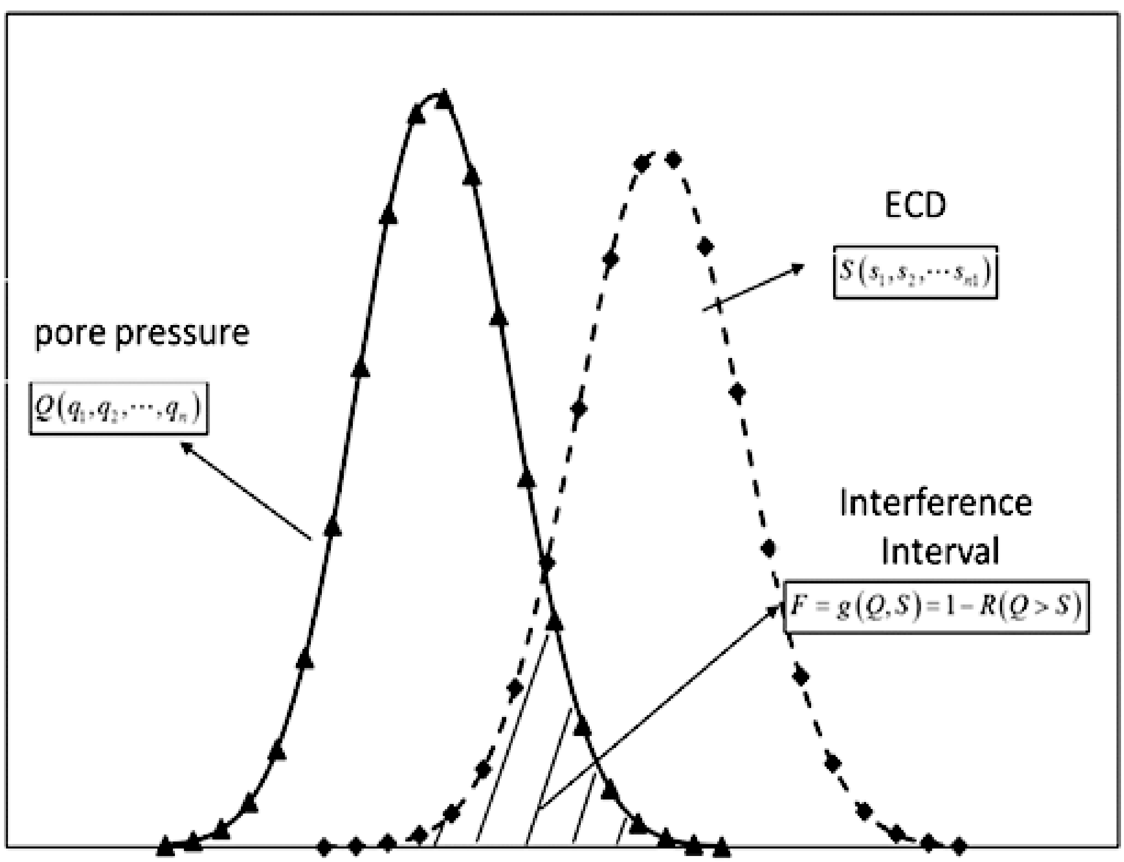

Fig. 2. Schematic diagram of well kick

$$F = 1 - R \tag{3}$$

Where, F is the drilling engineering risk. R is probability that the function of the drilling fluid does not fail. To calculate the risk probability of, we examined the interference in Figure 2, as depicted in Figure 3.

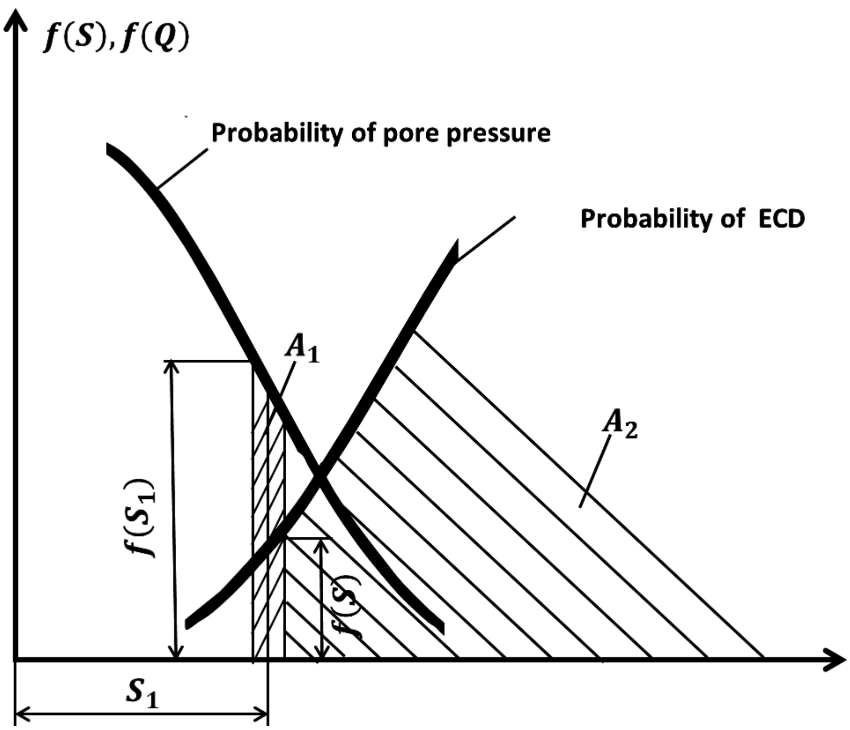

Fig. 3. Interference between pore pressure and ECD

According to Figure 3, the probability of pore pressure S_1 falling in the interval of $[S_1 - \frac{dS}{2}, S_1 + \frac{dS}{2}]$ is equal to the area of A1, given by the following formula:

$$P\left(S_1 - \frac{dS}{2} \le S_1 \le S_1 + \frac{dS}{2}\right) = f\left(S_1\right)dS = A_1 \tag{4}$$

The probability that the ECD is greater than the pore pressure is equal to the shaded area of A_2:

$$P\left(Q > S\right) = \int_{S_1}^{\infty} f\left(Q\right)dQ = A_2 \tag{5}$$

Equations (4) and (5) indicate the probabilities of the two independent events. The probability that these two events occur simultaneously is the safety probability, given by the following formula:

$$dR = A_1 A_2 = f\left(S_1\right)dS \times \int_{S_1}^{\infty} f\left(Q\right)dQ \tag{6}$$

The reliability of the drilling fluid function is the probability that ECD is greater than all possible pore pressure values.

$$R = \int_{-\infty}^{\infty} dR = \int_{-\infty}^{\infty} f\left(S\right)\left[\int_{S}^{\infty} f\left(Q\right)dQ\right]dS \tag{7}$$

Notably, the parameters in the ECD and pore pressure formulas are all random variables, given as follows:

$$Q = Q(x_{Q1}, x_{Q2}, \ldots, x_{Qn}) \tag{8}$$

$$S = \mathrm{S}(x_{S1}, x_{S2}, \ldots, x_{Sn}) \tag{9}$$

where x_{Qi} are random variables in the ECD formulas, such as drilling fluid static density, annulus pressure loss, and wellbore temperature and pressure. The terms x_{Si} are the random variables in the formulas of pore pressure, such as the overburden pressure, the Eaton index, the sonic log, the resistivity log or the normal compaction trend line. Therefore, the reliability and failure probability of the drilling fluid function can also be expressed as follows:

$$R = P\left(Z > 0\right) = \int_{0}^{\infty} f\left(Z\right)dZ = \int_{0}^{\infty}\int_{0}^{\infty} f_R\left(Z+S\right)f_S\left(S\right)dSdZ \tag{10}$$

$$F = P\left(Z < 0\right) = \int_{-\infty}^{0} f\left(Z\right)dZ = \int_{-\infty}^{0}\int_{-Z}^{\infty} f_R\left(Z+S\right)f_S\left(S\right)dSdZ \tag{11}$$

From the preceding analysis, given the probability distributions of ECD and pore pressure, the probability of reliability or drilling risk can be obtained. By assuming that the probability distributions of ECD and pore pressure both meet the normal distribution, the following formula is obtained:

$$f_Q\left(Q\right) = \frac{1}{\sigma_Q\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{Z-\mu_Q}{\sigma_Q}\right)^2\right] \quad -\infty < \sigma_Q < +\infty \tag{12}$$

$$f_S\left(S\right) = \frac{1}{\sigma_S\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{Z-\mu_S}{\sigma_S}\right)^2\right] \quad -\infty < \sigma_S < +\infty \tag{13}$$

where u_Q、u_S、σ_Q、σ_S are means and standard deviations of the two probability distributions. According to the theory of probability and mathematical statistics, the interference

$Z=Q-S$ of ECD and pore pressure also satisfies a normal distribution.

$$f(Z)=\frac{1}{\sigma_Z\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{Z-\mu_Z}{\sigma_Z}\right)^2\right] \quad -\infty<\sigma_Z<+\infty \tag{14}$$

where $\mu_Z=\mu_S-\mu_Q$, $\sigma_Z=\sqrt{\sigma_S^2+\sigma_Q^2}$.

When $Q>S$ *or* $Q-S>0$, drilling is safe. Therefore, the reliability is expressed as follows:

$$R=P(Z>0)=\int_0^{\infty}f(Z)dZ=\int_0^{\infty}\frac{1}{\sigma_Z\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{Z-\mu_Z}{\sigma_Z}\right)^2\right] \tag{15}$$

The probabilities of failure and reliability of drilling engineering are mutual inverse. Therefore, the probability of drilling risk is expressed as follows:

$$F=1-R=1-\int_0^{\infty}\frac{1}{\sigma_Z\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{Z-\mu_Z}{\sigma_Z}\right)^2\right]dZ \tag{16}$$

3. Results and discussion

N1 is a drilled well of the BD Madura gas field. In this block, we selected four wells with structures similar to that of N1: XX-1, XX-2, XX-3, and XX-4. We collected well logging data and calculated drilling geological and mechanical parameters. Based on the analysis method for formation pressure with credibility, the probability distributions of pore pressure and fracture pressure at a depth of 1800 m of N1 were calculated. The probability distributions were estimated to fit normal distributions, as illustrated in Figures 4 and 5. The probability distribution of ECD at 1800 m of N1 was obtained by analyzing ECD with credibility. The probability distribution was also estimated to fit a normal distribution, as illustrated in Figure 6.

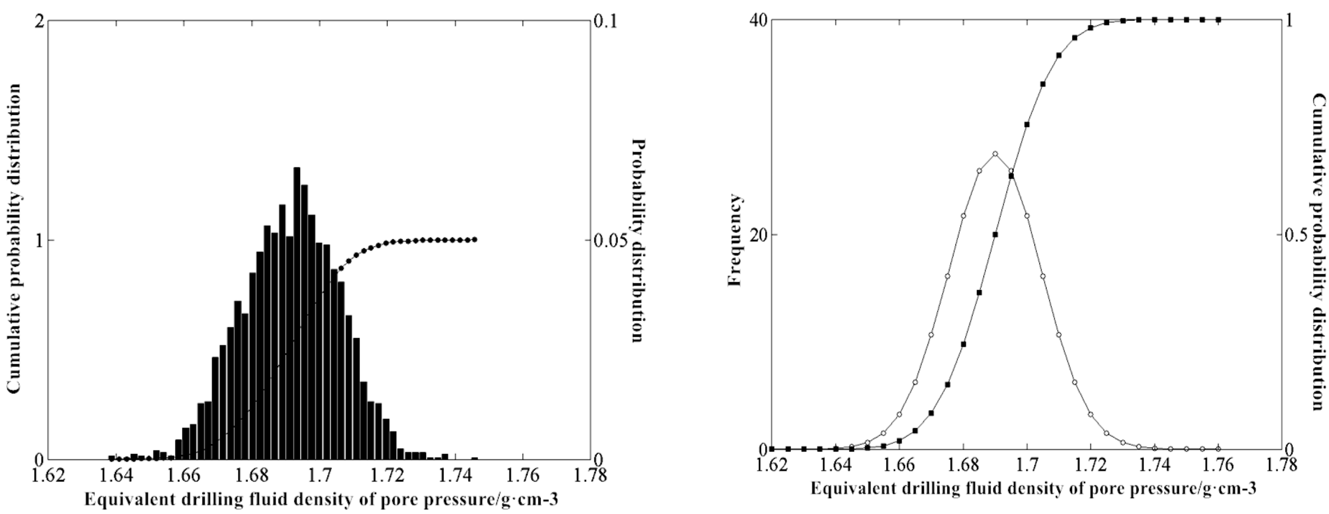

Fig. 4. Probability distribution of pore pressure

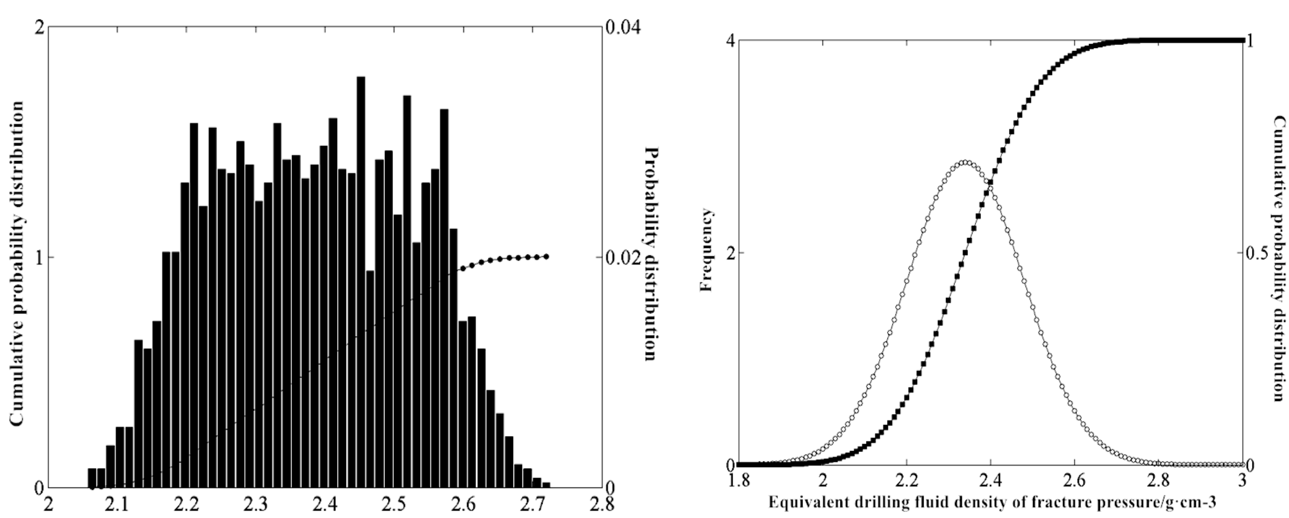

Fig. 5. Probability distribution of fracture pressure

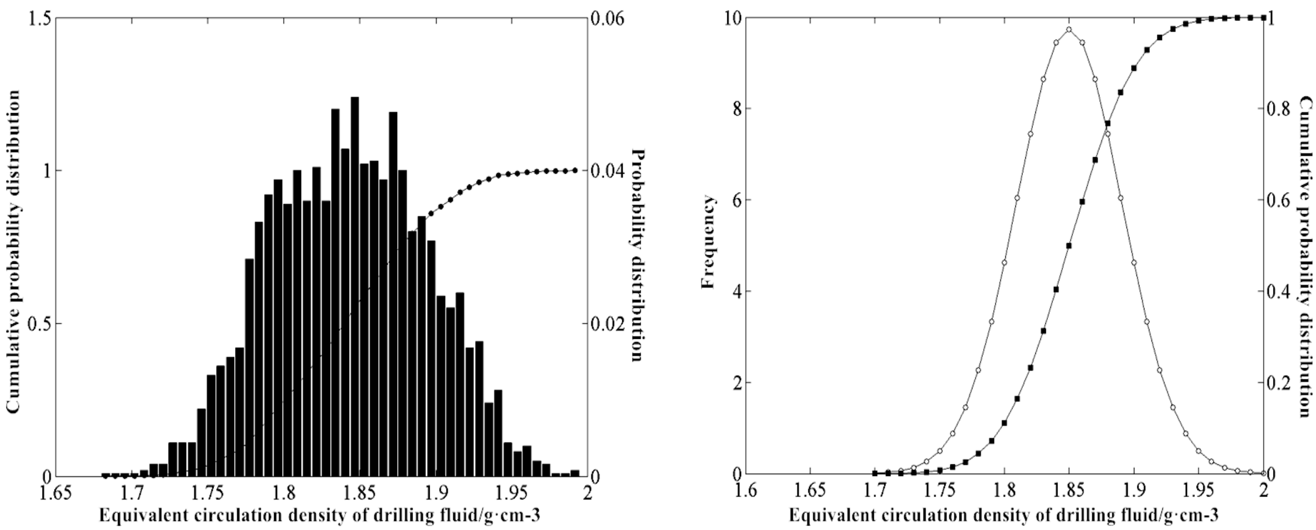

Fig. 6. Probability distribution of ECD

According to the daily well report, in the actual process, a well kick occurred, without a risk of well lost at the depth of 1800 m of N1 well. Based on the quantitative evaluation method for drilling risk, drilling risk at a well depth of 1800 m was evaluated and compared with the actual risk.

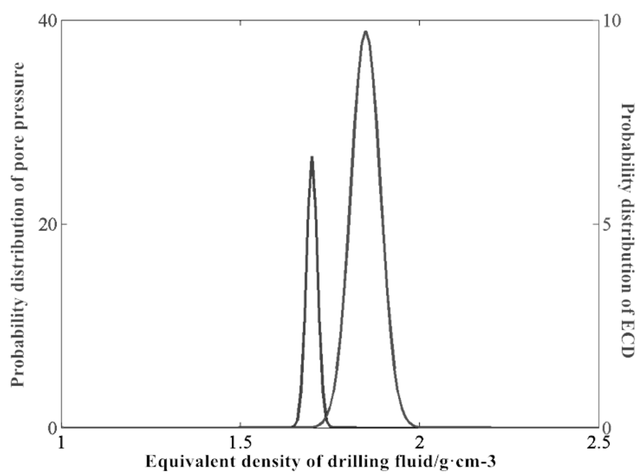

Fig. 7. Schematic diagram of well kick risk evaluation

At the depth of 1800 m of N1 well, the probability distribution of pore pressure was normal: u_Q=1.69, σ_Q=0.015. The probability distribution of ECD was also normal: u_S=1.85, σ_S=0.041. The distribution intervals of pore pressure and ECD were [1.65, 1.75] g/cm^3 and [1.7, 2.0] g/cm^3, respectively. Because the two probability distributions interfered with each other (Figure 7), well kick occurred. A MATLAB programmed calculated the reliability, R, as 0.41. Therefore, the probability of drilling risk was 0.59. In the actual process, a well kick occurred at the depth of 1800 m. The prediction results were in favorable agreement with the actual drilling risk.

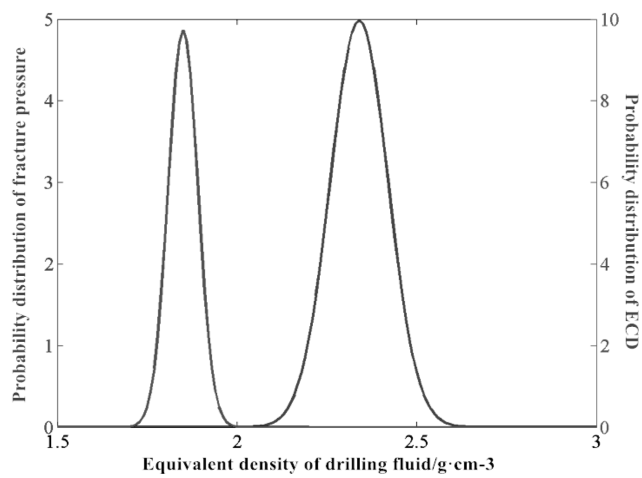

Fig. 8. Schematic diagram of well lost risk evaluation

In another case, at the depth of 1800 m of N1 well, the probability distribution of fracture pressure was normal: u_Q=2.34, σ_Q=0.08. The distribution intervals of fracture pressure and ECD were [2.2, 2.8] g/cm^3 and [1.7, 2.0] g/cm^3, respectively. The two probability distributions did not interfere with each other (Figure 8). No risk was noted. The prediction results were in favorable agreement with the actual drilling risk.

4. Conclusion

Uncertainties of drilling geological parameters, errors of measurement, and inaccuracies of computation model can lead to uncertain calculation of formation pressure. This can lead to unpredictable risks to the drilling design. Here, the uncertainty of formation pressure was analyzed, and a method of formation pressure determination with credibility was proposed.

The uncertainty of the ECD increases drilling risk. To manage this risk, this study presented the probability distribution of ECD based on the Monte Carlo simulation method.

Based on the generalized stress and strength interference theory, we established the quantitative evaluation method for drilling risk. In this method, the generalized stress was defined as the risk factor (ECD). The generalized intensity was defined as the safety factor or formation pressure. The function was defined as the risk function of drilling risk. In the two case studies, this method was used to predict drilling risk probabilities, and the prediction results were in favorable agreement with the actual drilling risk.

The current method can effectively help drill operations avoid and control drilling risk, which is conducive to the safety and efficiency of drilling operation.

5. Acknowledgements

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طريقة كمية جديدة لتقييم مخاطر الحفر اعتماداً على تحليل عدم اليقين

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الملخص

مع امتداد عمليات الحفر بعيداً عن الشاطئ أو في الأعماق والتكوينات المعقدة، تصبح عمليات الحفر أكثر خطورة. فالطرق التقليدية لا تضمن سلامة عمليات الحفر عالية المخاطر. ولذلك، فإن إنشاء طريقة كمية لتقييم مخاطر الحفر أصبح ملحاً. في هذا البحث، تم أولاً تحليل موثوقية ضغط التكوين وكثافة التدوير المكافئ (ECD) لسائل الحفر وفقاً لطريقة محاكاة مونت كارلو (Monte Carlo)؛ وتم الحصول على توزيعات الاحتمال لذلك. وبعد ذلك، واستناداً إلى نظرية الضغط المعمم وتداخل القوة، تم تحديد الطريقة الكمية لتقييم مخاطر الحفر. في هذه الطريقة، تم تعريف عامل الخطر على أنه الضغط المُعمم – كثافة التدوير المكافئ. وتم تعريف عامل الأمان على أنه الكثافة المُعممة – ضغط التكوين. وتم تعريف دالة حاجز الأمان بأنها دالة مخاطر الحفر. وفي دراستين مختلفتين، تم استخدام هذه الطريقة للتنبؤ باحتمالات مخاطر الحفر، وكانت نتائج التنبؤات متوافقة تماماً مع مخاطر الحفر الفعلية.