ENGINEERING RISK ASSESSMENT METHOD FOR UNDRILLED STRATA BASED ON DRILLING CONSTRUCTION PREVIEW

by

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With the development of the oil industry, the accuracy of the conventional well structure design method will be lower and lower. In order to ensure the smooth progress of drilling construction, this paper proposes a risk assessment method for the formation be drilled based on the equivalent drilling fluid density matrix, which reduces the use of empirical coefficients in the well structure design and realizes the fine design of the well structure.

Key words: *risk assessment of strata to be drilled, circulation drilling, drilling fluid circulation equivalent density*

Introduction

With the increasing demand for global oil and gas resources, the field of oil and gas exploration and development has gradually advanced from the middle and shallow layers to the deep and ultra-deep layers [1]. Deep and ultra-deep reservoirs have become an important strategic replacement field for increasing oil and gas reserves and production, and are also the focus of increasing reserves and production in the next few years [2]. With the gradual advancement of oil and gas drilling to the deep layer, the problem of safe running of casing with complex casing structure has become increasingly prominent [3].

In view of the strong uncertainty of deep formation information and the difficulty of quantitative evaluation of downhole engineering risk during drilling construction, Xu *et al.* [4] proposed a method to quantitatively characterize the uncertainty of formation pressure by using credibility, and on this basis, a quantitative evaluation method of engineering risk was established, fig. 1. However, this method is more suitable for post-evaluation of drilled wells.

The equivalent cyclic density physical calculation method

The down drilling condition reads [5]:

$$\mathrm{ECD} = \mathrm{ESD} = \frac{P\left(L,\rho\right)}{\mathrm{g}L} = \frac{P_0 + \int\limits_{L0}^{L} \rho \mathrm{g} \mathrm{d}L}{\mathrm{g}L} \tag{1}$$

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where L is the vertical depth, $P(L, \rho)$ – the static pressure, ρ – the density of drilling fluid in the well, g – the gravitational acceleration, P_0 – the wellhead pressure, and $\int_{L0}^{L} \rho \text{g} \text{d}L$ – the hydrostatic column pressure.

The circulation drilling condition is given [6]:

$$\text{ECD} = \frac{P_a}{\text{g}h} = \frac{P_{\text{sea}} + P_{as} + P_a}{\text{g}h} = \frac{\rho_{\text{sea}} h_0 \text{g} + \rho_m \left(h - h_0\right)\text{g} + P_a}{\text{g}h} = \rho_{\text{sea}} \frac{h_0}{h} + \rho_m \left(1 - \frac{h_0}{h}\right) + \frac{P_a}{\text{g}h} \tag{2}$$

where ECD is equivalent cyclic density, P_a – the bottom hole pressure, h – the well depth, P_{sea} – the hydrostatic column pressure of seawater, P_{as} – the hydrostatic column pressure in the annulus, ΔP_a – the pressure loss of annular circulation, ρ_{sea} – the density of seawater, h_0 – the depth of seawater, and ρ_m – the density of the drilling fluid.

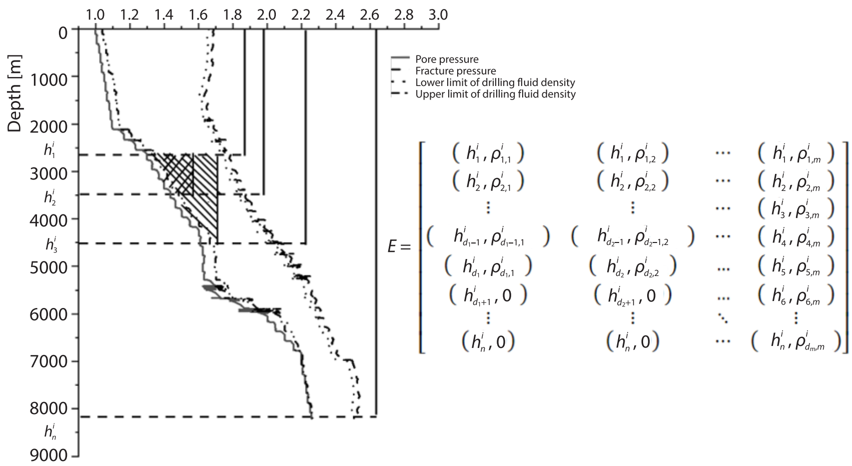

Figure 1. Schematic diagram of ECD matrix

Under the condition of tripping, the faster the tripping speed is, the greater the transient pumping excitation pressure at the bottom of the well is, and the greater the influence on ECD is [7].

– The wellbore flow rates under different working conditions are calculated, respectively:

$$\begin{aligned} &\text{Plugging pipepump stop } \bar{v} = \left(\frac{d^2}{D^2 - d^2} + K_c\right) v_p \\ &\text{Open pipeline (pump stop) } \bar{v} = \left(\frac{d^2 - d_i^2}{D^2 - d^2} + K_c\right) v_p - \frac{40Q_i}{\pi\left(D^2 - d^2\right)} \\ &\text{Open pipelin (pump open) } \bar{v} = \left(\frac{d^2}{D^2 - d^2} + K_c\right) v_p + \frac{40Q_p}{\pi\left(D^2 - d^2\right)} \end{aligned} \tag{3}$$

where d is the outer diameter of the drill pipe, D – the borehole diameter, K_c – the adhesion coefficient, v_p – the downward speed of the drill pipe, d_i – the inner diameter of the drill pipe, Q_i – the flow rate of drilling fluid entering the drill pipe, and Q_p – the flow rate of drilling fluid pumped by mud pump.

– The fluctuating pressure caused by POOH and RIH reads:

$$P_{sw} = \frac{0.196 f_m \rho_m \bar{v}^2 L_i}{D - d} \tag{4}$$

where P_{sw} is the fluctuating pressure, f_m – the friction coefficient, and L_i – the length of drill pipe.

– The wellbore ECD under POOH and RIH condition reads:

$$\mathrm{ECD} = \frac{P_a}{\mathrm{g}h} = \frac{P_{\mathrm{sea}} + P_{as} + P_{sw}}{\mathrm{g}h} = \frac{\rho_{\mathrm{sea}} h_0 \mathrm{g} + \rho_m (h - h_0)\mathrm{g} + P_a}{\mathrm{g}h} = \rho_{\mathrm{sea}} \frac{h_0}{h} + \rho_m \left(1 - \frac{h_0}{h}\right) + \frac{P_a}{\mathrm{g}h} \tag{5}$$

where P_a is the annular pressure, P_{sea} – the seawater pressure, P_{as} – the land pressure, P_{sw} – the annular pressure loss, and h_0 – the land depth.

Principle of equivalent cyclic density matrix model

The annulus pressure ECD in the open hole section changes dynamically during drilling. The open hole section is drilled from the formation the completion of the casing, and the entire wellbore annulus will experience a series of annulus pressure ECD from top to bottom at each depth point. Therefore, in the process of drilling engineering risk assessment, it is necessary to fully consider the variation range of open-hole annulus pressure in the whole drilling cycle, and put forward the concept of open-hole annulus ECD matrix *Ei*, which includes wellbore depth and equivalent drilling fluid density of open-hole annulus pressure in the whole drilling cycle.

The open hole annulus ECD matrix *Ei* is composed of the open hole well depth and the open hole annulus ECD, and the superscript i denotes the open hole. The open hole well depth sequence $\{h^i_1, h^i_2, h^i_3,...h^i_n\}$is the fixed interval sequence between the upper casing shoe and the drilling depth of the open hole; In order to simplify the calculation process, the wellbore annulus ECD is calculated only when the drilling fluid process parameters are changed. If the drilling fluid process parameters are unchanged, the annulus ECD of the upper drilled open hole section is a fixed value, and the bottom hole depth index sequence when calculating the annulus ECD is $\{d_1, d_2, d_3,..., d_m\}$. In particular of $d_m = n$, it means that the ECD of the open hole annulus is calculated when the drilling is completed, in other words, the number of rows n of the *Ei* matrix represents the length of the well depth sequence, the number of columns m represents the number of calculations of the wellbore annulus ECD, and the element ρ of each column represents the result of the calculation of the open-hole annulus ECD, while the ECD value corresponding to the undrilled formation depth is 0.

The open-hole annulus ECD matrix of the whole well section is established in turn, and the maximum and minimum values of the open-hole annulus ECD matrix are taken horizontally, so as to obtain the maximum matrix $P_{d\max}$ of the open-hole annulus ECD of the whole well section and the minimum matrix $P_{d\min}$ of the open-hole annulus ECD of the whole well section.

$$P_{d\max} = \begin{bmatrix} h_1 & h_2 & h_3 & \cdots & h_n \\ \rho_{d\max 1} & \rho_{d\max 2} & \rho_{d\max 3} & \cdots & \rho_{d\max n} \end{bmatrix}^{\mathrm{T}} \tag{6}$$

$$P_{d\min} = \begin{bmatrix} h_1 & h_2 & h_3 & \cdots & h_n \\ \rho_{d\min 1} & \rho_{d\min 2} & \rho_{d\min 3} & \cdots & \rho_{d\min n} \end{bmatrix}^{\mathrm{T}} \tag{7}$$

where $P_{d\max}$ is the maximum value of annular pressure, $P_{d\min}$ – the minimum value of annular pressure, $\rho_{d\max i}$ – the maximum cyclic densities at the corresponding depth, and $\rho_{d\min i}$ – the minimum cyclic density at the corresponding depth.

Quantitative evaluation method of drilling engineering risk

The quantitative risk evaluation method of drilled well engineering based on wellbore pressure balance criterion is a mature method, which is proposed by the team of Professor Guan Zhichuan of China University of Petroleum (East China). If the discussion is carried out, its content can form a rich doctoral dissertation. Therefore, due to the length of the article, only the methods used in this article are discussed here, and the more detailed methods can refer to the relevant [8, 9].

The generalized stress and strength interference theory is the basic theory for structural strength safety analysis. In this theory, the generalized stress is defined as the failure factor, the generalized strength is defined as the factor to prevent the failure of the system, and the function between the generalized stress and the strength is defined as the performance function. The reliability or failure probability of the system can be determined by solving the performance function. The hazard factor is set to $Q(q_1, q_2, q_3,..., q_n,)$, the intensity factor is set to $S(s_1, s_2, s_3,..., s_n,)$, the safety factor is set to $R(r_1, r_2, r_3,..., r_n,)$, and the risk function is suggested [10]:

$$F = \mathrm{g}(Q, S) = 1 - R(Q > S) \tag{8}$$

According to the mechanism of drilling risk, we define the pressure of drilling fluid column in wellbore as the risk factor. The upper and lower limits of safe drilling fluid density window are defined as safety factors. The performance function is defined as the risk function of underground complexities and accidents [11].

The probability R that the equivalent density of drilling fluid is greater than the lower limit of well kick prevention:

$$R = P(Q > S) = P(Q - S > 0) = P\left(\frac{Q}{S > 1}\right) \tag{9}$$

where Q is a random variable of the equivalent density of drilling fluid, and S is a random variable of the lower limit of well kick prevention. If the previous formula can be satisfied, the function of drilling fluid to maintain bottom hole pressure balance is reliable, otherwise risks will occur.

The equivalent circulation density, Q, of drilling fluid and the lower limit value S of well kick prevention are both in probability distribution. When the two probabilities interfere, it indicates that there will be a risk:

$$F = 1 - R \tag{10}$$

According to the aforementioned method, the probability calculation formula of drilling risk R_k can be obtained:

$$R_{\mathrm{k(h)}} = P\left(\rho_\mathrm{d} < \rho_{\mathrm{k(h)}}\right) = 1 - F_{\rho_{\mathrm{k(b)}}}\left(\rho_\mathrm{d}\right) \tag{11}$$

where $R_{\mathrm{k(h)}}$ is the risk of well kick, ρ_d – the drilling fluid density at the time of drilling, and $\rho_{\mathrm{k(h)}}$ – the equivalent density of the well kick.

The risk of well leakage R_L is given:

$$R_{\mathrm{L(h)}} = P\left(\rho_\mathrm{d} > \rho_{\mathrm{L(h)}}\right) = F_{\rho_{\mathrm{L(b)}}}\left(\rho_\mathrm{d}\right) \tag{12}$$

where $R_{\mathrm{L(h)}}$ is the risk of well leakage at depth h and $\rho_{\mathrm{L(h)}}$ – the equivalent density of the well leakage.

The risk of wellbore collapse $R_{c(h)}$ is suggested:

$$R_{c(h)} = \max\left\{P\left(\rho_d < \rho_{cl(h)}\right), P\left(\rho_d > \rho_{c2(h)}\right)\right\} = \max\left\{1 - F_{\rho_{c(b)}}\left(\rho_d\right), F_{\rho_{c2(b)}}\left(\rho_d\right)\right\} \tag{13}$$

where $R_{L(h)}$ is the risk of well leakage at depth h and $\rho_{c2(h)}$ – the equivalent density of the well leakage.

The risk of bit freezing of differential pressures R_{sk} reads:

$$R_{sk(h)} = P\left(\rho_d < \rho_{sk(h)}\right) = F_{\rho_{sk(h)}}\left(\rho_d\right) \tag{14}$$

where $R_{sk(h)}$ is the risk of differential pressure sticking at depth h and $\rho_{sk(h)}$ – the equivalent density of the differential pressure sticking.

The equivalent cyclic density matrix risk assessment of formation be drilled

Because different downhole risks have different risk-causing mechanisms, their risk locations are also different. Therefore, the formation three pressure matrix, *P*, is constructed by splicing the formation three pressure monitored while drilling in the drilled section from the lower part of the casing shoe to the bit and the predicted formation three pressure in the pre-exploration interval of the formation be drilled. On this basis, combined with the maximum and minimum vectors of open hole annulus ECD, the dynamic early warning of downhole risk is carried out by the quantitative evaluation method of drilling engineering risk based on reliability theory. By using the drilled wells as a reference, we reconstructed the ECD matrix of the lower formation be drilled in the M2 well. In this process, we use the Eaton method combined with the Fillippone method to predict the formation pressure. Through the determination of the relevant parameters of rock mechanics and physical properties of several other drilled wells, the statistics and range of parameter values, the range of formation collapse and fracture pressure values is calculated by direct theory.

Because different downhole risks have different risk-causing mechanisms, their risk locations are also different. For example, overflow generally occurs at the drill bit, and lost circulation generally occurs at the upper casing shoe or weak layer. Therefore, the formation three pressure matrix P is constructed by splicing the formation three pressure monitored while drilling in the drilled section from the lower part of the casing shoe to the bit and the predicted formation three pressure in the pre-exploration interval of the formation be drilled. On this basis, combined with the maximum and minimum vector of ECD in the open-hole annulus, the dynamic early warning of downhole risk is carried out by the quantitative evaluation method of drilling engineering risk based on reliability theory. The final map is as follows.

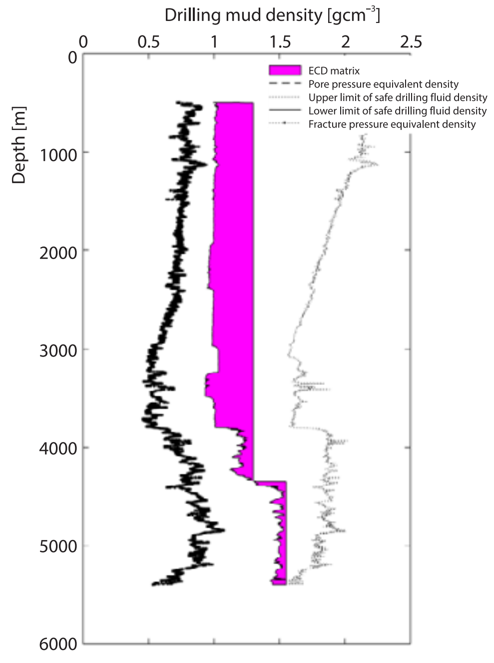

Figure 2. The ECD matrix graph

Based on this, we introduced the ECD matrix calculation method. By using the wellbore pressure matrix model and the wellbore pressure risk assessment method, the risk probability of downhole accidents was obtained. From the results of the fig. 2, we can clearly see that at about 5300 m, drilling construction will have a great risk of lost circulation. In fact, lost circulation also occurred during drilling of well M2. This means that through the ECD matrix method of the formation be drilled, we can more accurately predict the downhole risks that may occur during drilling, which will help the smooth progress of drilling construction and save costs.

Conclusion

By introducing the quantitative evaluation method of downhole risk of Guan team, the downhole complex risk probability profile rich in geological-engineering information is obtained, which solves the problem of insufficient generalization ability of the model due to the small number of risk samples.Focus on solving the problem of difficult risk prediction of the lower formation be drilled in the process of drilling construction, especially when the target block is generally drilled in ultra-deep wells greater than 5000 m, this method cannot only reduce the conservative degree of the conventional empirical coefficient method, but also obtain relatively more accurate risk assessment results.The method of risk assessment in drilling process by ECD matrix is proposed, and the risk assessment is carried out by *wellbore pressure matrix* instead of *static drilling fluid density + empirical coefficient*. The calculation example shows that the results of risk assessment by ECD matrix method are relatively accurate.

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Nomenclature

d – outer diameter, [Nm^{-2}]
L – vertical depth, [m]
P_0 – torque, [MPa]
$P(L, \rho)$ – static pressure, [MPa]

Greek symbol

ρ – density, [kgm^{-3}]

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