Probability analysis method for well kick under uncertain formation pressure conditions

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Abstract. Drilling safety and efficiency are greatly impacted by kick, a major problem that is hard to diagnose, assess, and predict due to the complexity and high uncertainty of the deep water drilling formation pressure system. This article forms a pre-drilling well kick probability prediction method by establishing a calculation model for wellbore ECD and using the numerical solution method of Monte Carlo simulation algorithm. The bottomhole pressure uncertainty range gradually increases with well depth, according to simulation calculations, and the probability of a well kick decreases with drilling fluid volume. Theoretically, safe well control in deepwater drilling can be guided by the well-established kick diagnosis and formation pressure assessment techniques.

Keywords: Formation pressure uncertainty, Monte Carlo simulation, well kick, probability.

1. Introduction

The safe and effective development of China's vast deepwater oil and gas reserves is essential to guaranteeing the country's energy security. The complexity and unpredictability of deep-water geological processes and the marine environment have made it increasingly challenging to identify and assess well surges. Massive casualties and property destruction will result from a blowout. In contrast to onshore well control, wellbore pressure and formation information uncertainty are major problems in diagnosing and evaluating well kick in deepwater drilling.

Probability analysis and quantitative risk assessment are frequently used in engineering situations with uncertain parameters to identify potential hazards and evaluate the likelihood of hazard occurrence. Cowan proposed a quantitative risk assessment model for oil and gas reservoir exploration and development in 1969 [1], combining probabilistic geological, engineering, and economic parameters with potential benefits. Thorogood developed a "decision tree" for wellbore instability issues in 1991 [2] and produced a quantitative risk assessment model in tandem. In 2001, Nilsen introduced the "KickRisk" quantitative risk assessment model for overflow [3], which established a corresponding decision tree model for the situation after wellbore loss of control from two aspects: well closure and re control. In 2002, Liang et al. [4] proposed a quantitative risk assessment method (QRA) for predicting pore pressure and formation fracture pressure gradient, which predicted the probability distribution of pore pressure, equivalent drilling fluid density, and formation fracture pressure gradient based on Gaussian distribution. In 2012, Skogdalen et al. [5] conducted a risk assessment of the Deepwater Horizon platform blowout accident in the Gulf of Mexico from four aspects: external environmental risk, geological condition risk, technical risk, and construction process risk. In 2013, Khakzad et al. established an "event tree" model for deepwater drilling kick and blowout [6], and quantitatively evaluated their risk using the bow tie model and Bayesian model. However, in the above-mentioned studies, there is still no kick possibility quantitative evaluation occurrence by combining wellbore flow mechanism models with probability analysis methods for deepwater drilling conditions. This paper creates a wellbore ECD calculation model based on prior research and integrates a Monte Carlo simulation approach to create a pre-drilling well kick probability prediction tool.

2. Fundamentals of Quantitative Analysis of Pre drilling Kick Probability

The quantitative risk analysis method is a widely used technique in engineering that has been progressively adopted in many drilling engineering fields, including casing structure design, drilling engineering design, quantitative risk assessment of well kick, and so forth.

In order to determine the joint probability distribution of pore pressure density and drilling fluid equivalent circulation density, while using quantitative risk analysis methodologies for pre-drilling well kick quantitative risk assessment, each input parameter's uncertainty must be considered. Unpredictability in the drilling fluid actual equivalent circulating density, which is often dependent on the mud's density, rheology, pipe wall friction coefficient, and flow velocity.

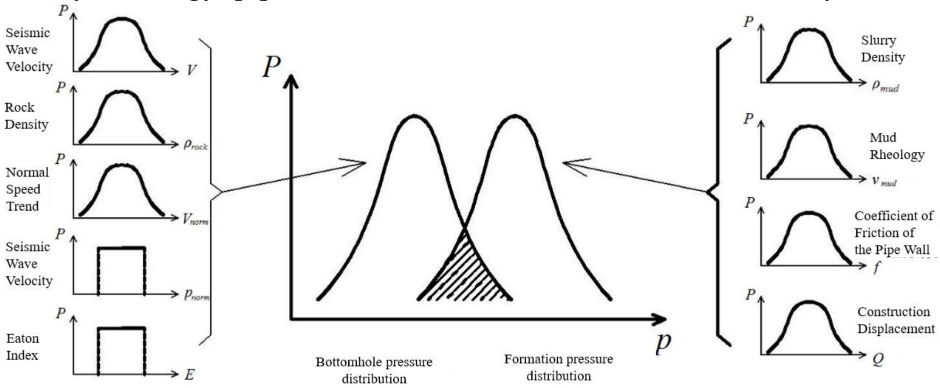


Fig.1-1 Schematic of kick probability analysis (P: probability； p:pressure)

Figure1-1 illustrates the probability distribution that both the formation pore pressure and bottomhole pressure are expected to follow under typical circumstances. Two overlapping distribution curve indicates the possibility of kick, which happens when the formation pore pressure is higher than the bottom hole pressure. Apply quantitative risk analysis techniques to quantify the well-kick's risk value (R_K). The safety factor of the formation pore pressure at that depth is low, and there is a 25% risk of a well kick happening, for instance, if the RK of a well at a given depth is 25%.

3. Deepwater drilling downhole equivalent density calculation method

3.1 Drilling fluid density prediction model

Empirical and composite component models are currently the most widely utilized drilling fluid density prediction models in the petroleum sector. Hoberock et al.'s model [7], which takes into account how the component densities of solid, oil, and water vary with pressure and temperature, respectively, represents the composite component model. Regression analysis using experimental data and specific theoretical forms is the primary method used to create the empirical model. Models by Guan Zhichuan, Yan Jienian, and others are exemplary.

This article uses the following model for calculation [8],

$$\rho = \rho_0 \times \exp[\theta(P,T)] \tag{2-1}$$

This paper focuses on the effects of temperature and pressure interactions, elastic compression affected by pressure changes, and thermal expansion affected by temperature changes, all based on the original model. This pattern is caused by the approximately uniform distribution of formation temperature and pressure changes at different depths and fluid temperature and pressure changes.

$$\exp[\theta(P,T)] = \gamma_P P_{dient} H + \gamma_{PP}(P_{dient}H)^2 + \gamma_T T_{dient} H + \gamma_{TT}(T_{dient}H)^2 + \gamma_{PT} P_{dient} T_{dient} H^2 \tag{2-2}$$

In the formula: γ_P、γ_{PP}—equation coefficients related to elastic compression,1/Pa,1/Pa2;

γ_T、γ_{TT}—equation coefficients related to thermal expansion,1/°C,1/°C2;

γ_{PT}—equation coefficients affected by temperature and pressure interaction,1/ (Pa·°C);

P_{dient}、T_{dient}—formation pressure gradient and temperature gradient,Pa/m,°C/m.

3.2 Prediction model for drilling fluid viscosity

The temperature field fluctuations impact the change in wellbore drilling fluid viscosity, and pressure variations. Among them, the American Petroleum Institute suggests a calculating drilling fluids' effective viscosity method at various pressure and temperature settings [9],

$$\mu_C(t_2)=\mu_C(t_1)\exp\left(\alpha\left(\frac{t_2-t_1}{t_2t_1}\right)\right) \tag{2-3}$$

$$\mu_C(p_2)=\mu_C(p_1)\exp\left(\beta(p_2-p_1)\right) \tag{2-4}$$

In the formula: $\mu_C(t_1)$、$\mu_C(t_2)$—effective viscosity at temperature t1 and t2,Pa·s;

$\mu_C(p_1)$、$\mu_C(p_2)$—effective viscosity at p1 and p2,Pa·s;

α、β—temperature constant.

Yan Jienian et al. studied the rheological properties of water-based and oil-based drilling fluids and obtained a universal calculation equation as follows [7],

$$\mu=\mu_0\times\exp[\theta(P,T)] \tag{2-5}$$

Calculation error ranging from -4.76% to 5.43%, water-based drilling fluid equation is as follows:

$$\mu=39.45\times\exp\left[(-4.2788\times10^{-3}T)+(5.2767\times10^{-2}P)\right] \tag{2-6}$$

Oil-based drilling fluid equation form is as follows, with a calculation error between -5.91% and 5.91%,

$$\theta(P,T)=A(T-T_o)+B(P-P_o)+C(T-T_o)(P-P_o)+D(T-T_o)^2 \tag{2-7}$$

3.3 Calculation of equivalent circulating density of drilling fluid

The equivalent circulation density of drilling fluid can be calculated from the flow parameters in the drill pipe or annulus. Considering the two-phase flow process of oil and gas in the vertical direction, assuming that the fluid temperature is equal to the surrounding seawater or formation temperature, based on the principles of mass and momentum conservation, corresponding continuity equations and momentum conservation equations are obtained.

$$\frac{\partial}{\partial z}(A\rho_l\alpha_lv_l)=0 \tag{2-8}$$

$$\frac{\partial}{\partial z}(A\rho_g\alpha_gv_g)=q_{wb} \tag{2-9}$$

$$\frac{\partial P}{\partial z}=-\left(\rho_l\alpha_l+\rho_g\alpha_g\right)g-\frac{\Delta P_f}{\Delta z} \tag{2-10}$$

Equations (2-8) and (2-9) represent the continuity equations for the liquid and gas phases, while equations (2-10) represent the corresponding momentum conservation equations.

The above equation contains seven unknown variables, namely ρ_l、α_l、v_l、ρ_g、α_g、$v_g$and P. In order to perform numerical solutions, other auxiliary equations are needed. The equation describing porosity and density of each phase is as follows

$$\alpha_l+\alpha_g=1 \tag{2-11}$$

$$\rho_l=\rho_l(p,T) \tag{2-12}$$

$$\rho_g=\rho_g(p,T) \tag{2-13}$$

In the formula: ρ_l—the density of mud, kg/m3; ρ_g—density of gas, kg/m3; a_l—cross-sectional liquid holdup,0~1; a_g—cross section gas content,0~1.

Using drift models to describe the relative transport of gas and liquid phases,

$$v_g=Kv_m+S=K\left(v_{ls}+v_{gs}\right)+S \tag{2-14}$$

In the formula: K—distribution coefficient,0~1; S—slip coefficient, m/s.

Pressure drop in annular friction is a flow velocity, density, and friction coefficient function,

$$\frac{\Delta P_f}{\Delta z}=\frac{2f\rho_mv_m^2}{(d_o-d_i)} \tag{2-15}$$

$$\text{Re} = \frac{\rho_m v_m (d_o - d_i)}{\mu_m} \quad (2\text{-}16)$$

In the formula, f is the friction coefficient. When $\text{Re} \geq 3500$, $f = 0.052\text{Re}^{-0.19}$; When $\text{Re} \leq 2000$, $f = 24/\text{Re}$; when $2000 \leq \text{Re} \leq 3500$, it is in a transitional state of laminar turbulent flow, and interpolation calculation is performed.

4. Probability analysis of well kick based on Monte Carlo simulation

The Monte Carlo method, also known as random sampling test or statistical test method, is widely used in probability analysis. According to data from a deep-water example well, the depth is 3500 metres. Table 3-1 illustrates the uncertainty in mud density, viscosity, and pipe wall friction coefficient [10]. Based on this, the Monte Carlo approach is used to generate the distribution profile of equivalent circulation density of drilling fluid in the wellbore, which, when paired with formation pressure uncertainty analysis results, predicts the probability of well kick.

Table 3-1 Uncertainty distribution of ECD model parameters

Variable	Uncertainty	Variable	Parameter values
viscosity	$\mu = \text{N}(1,0.05)$	displacement	30 L/s
density	$\rho = \text{N}(1,0.05)$	Inner diameter of annulus	5-1/2 in
Friction coefficient	$f_c = \text{T}(0.9,1,1.1)$	Outer diameter of annulus	9-5/8 in

4.1 3.1 ECD uncertainty analysis results

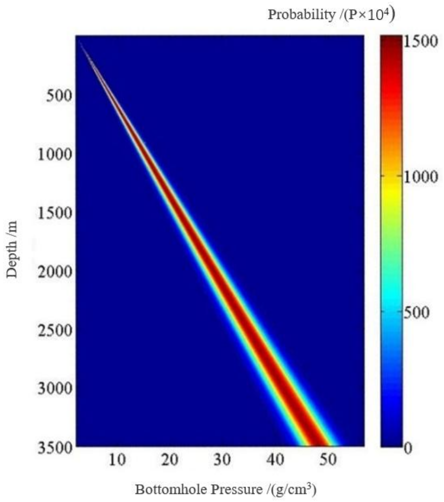


Fig.3-1 Uncertainty analysis of mud ECD along the wellbore

Figure 3-1 shows, with the well depth increase, the uncertainty range of bottomhole pressure gradually increases. Its calculation accuracy can be corrected by measuring the bottomhole pressure value or establishing more accurate density, viscosity, and friction coefficient calculation models.

4.2 3.2 Well gushing probability calculation

The acoustic wave propagation time was measured from N = 170 measurement locations at depths ranging from 500 to 3500 m. The nominal precision of the collected propagation time is 0.1ms, the waveform is digitized every 1ms, and the main wavelength of the seismic signal is around 20m. The model has M = 400 uniform layers with a depth range of 105-3500 meters. Figure 3-2 depicts the seismic wave's propagation time as measured by the receiver.

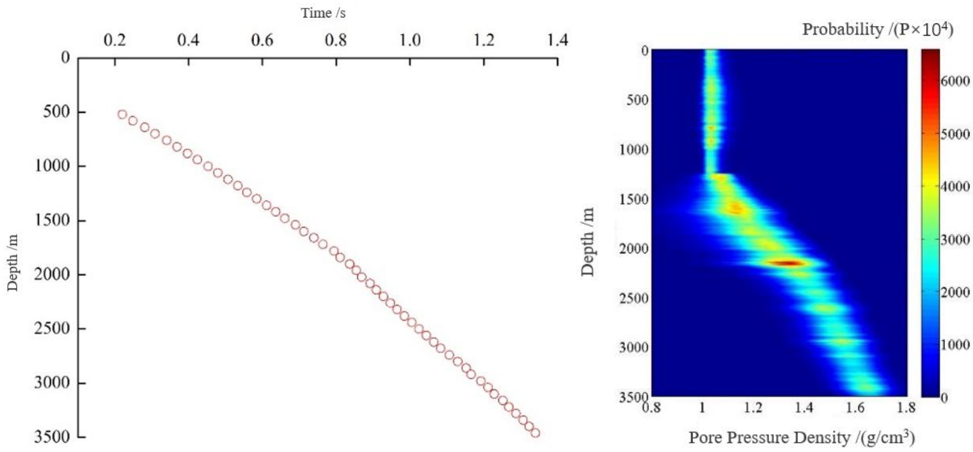
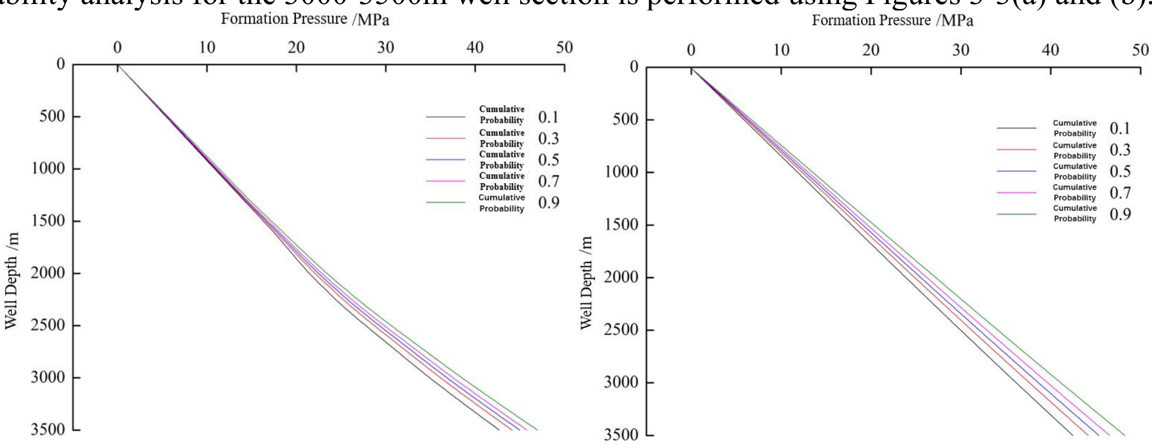


Figure 3-2 Seismic wave propagation time and formation pressure prediction profile

In the above example well, the open-hole interval is 3000m-3500m. Assuming that there is a permeability horizon at every 100m in the 3000m≤D≤3500m section, the horizons corresponding to the depth of 3100m, 3200m, 3300m, 3400m and 3500m are recorded as the 1st, 2nd, 3rd, 4th and 5th horizons. According to the algorithm proposed in this paper, the probability of well gushing is predicted by combining the probability distribution of formation pressure and the probability distribution of bottomhole pressure.

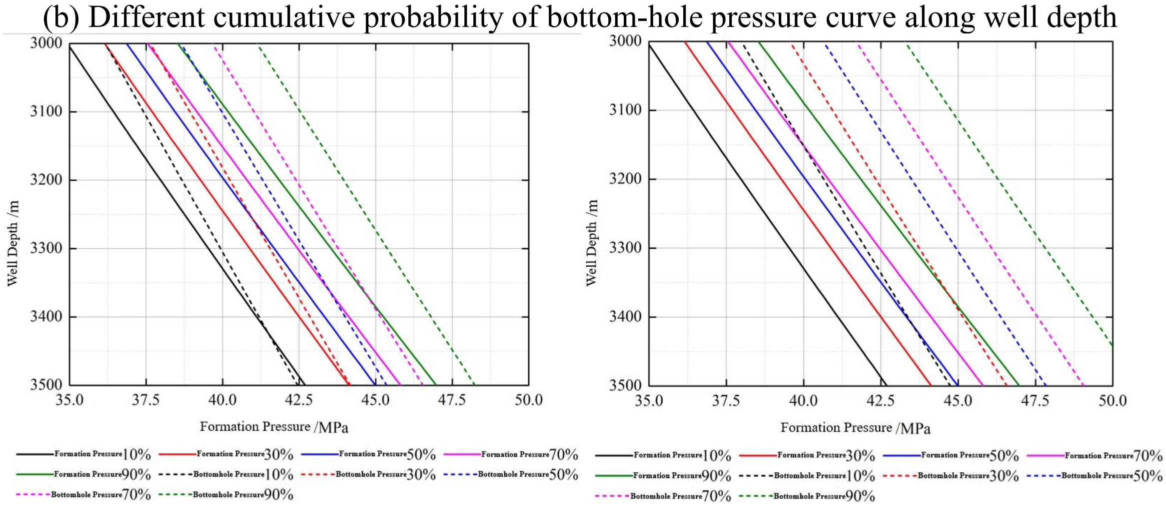
Figure 3-3 (a) and (b) depict the formation and wellbore pressure probability distribution curves respectively. According to the simulation results in probability and statistics, yielding distribution curves with cumulative probabilities of 0.1, 0.3, 0.5, 0.7, and 0.9, respectively. The well gushing probability analysis for the 3000-3500m well section is performed using Figures 3-3(a) and (b).



(a) (b)

Fig.3-3 (a) Pore pressure curve along well depth under different accumulation probability

(b) Different cumulative probability of bottom-hole pressure curve along well depth



(a) (b)

Fig.3-4(a) Kick probability analysis when Q=30L/s

Fig.3-4(b) Kick probability analysis when Q=50L/s

Figure 3-4(a)(b) shows the results of well surge probability analysis at 30 L/s and 50 L/s. It can be seen from the figure that if there are any two formation pressure curves with a cumulative probability of P_1($0 \le P_1 \le 1$)and a bottomhole dynamic pressure curve with a cumulative probability of P_2 ($0 \le P_2 \le 1$)for a specific wellwell well, the probability of the occurrence of the wellwell gushing is not zero. The farther apart the two curves with the same cumulative probability (the formation pressure curve is on the left), the smaller the probability of well surge occurring. In addition, the slope of the formation pressure curve is greater than that of the bottomhole dynamic pressure curve, so the probability of well surge gradually decreases with the increase of well depth.

Taking Fig. 3-4(a)(b) as an example, the well gushing P_{k1}, P_{k2}, P_{k3},P_{k4},P_{k5} probability and the overall risk R_{K-T} of each horizon under different displacements are calculated. Table 3-2 shows some results.

According to the relationship between drilling fluid discharge and the overall risk in Table 3-2, Figure 3-5 shows the following factors:

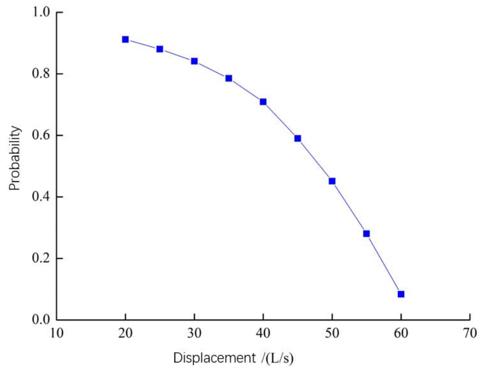


Fig.3-5 Curve of total kick probability varies with discharge capacity in the open hole section

Table 3-2 Calculation results of kick probability with different discharge capacities

Drilling fluid displacement	Q=20L/s	Q=30L/s	Q=40L/s	Q=50L/s	Q=60L/s
P_{k1}	0.195	0.161	0.12	0.071	0.0125
P_{k2}	0.286	0.232	0.171	0.093	0.0148
P_{k3}	0.383	0.309	0.223	0.118	0.0174
P_{k4}	0.466	0.375	0.265	0.134	0.0201
P_{k5}	0.534	0.427	0.301	0.147	0.0216
R_{NK-T}	0.0882	0.1594	0.2912	0.5490	0.9165
R_{K-T}	0.9118	0.8406	0.7088	0.4510	0.0835

Figure 3-5 shows the relationship curve between drilling fluid displacement and well surge risk value in the entire open-hole section. The overall well surge probability in the whole open-hole horizon under different displacements was evaluated. It can be seen from the figure that with the increase of drilling fluid discharge, the total probability of well surge in the well gradually decreases from 1 to close to 0. Therefore, in formations with a high probability of well surge, in addition to increasing the density of drilling fluid, paying close attention to the signs of well surge and controlling the discharge of drilling fluid in time are the fastest and effective treatment measures to reduce the risk of well surge and avoid blowout.

5. Summary

(1) A pre-drilling blowout probability prediction method is established by combining the dynamic ECD model, formation pressure uncertainty analysis and Monte Carlo simulation.

(2) A simulation is performed to examine how the recorded pressure data affects the ECD posteriori distribution. This sets the stage for analyzing blowout risk in various scenarios.

(3) As the well depth deepens, the simulation findings indicate that the bottomhole pressure uncertainty range increasingly widens. The likelihood of a well surge diminishes with increasing drilling fluid displacement. A quick and efficient treatment method to lower the danger of well surge and prevent blowout in formations with a high probability of well surge is to promptly manage the drilling fluid discharge in addition to raising the density of the fluid.

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