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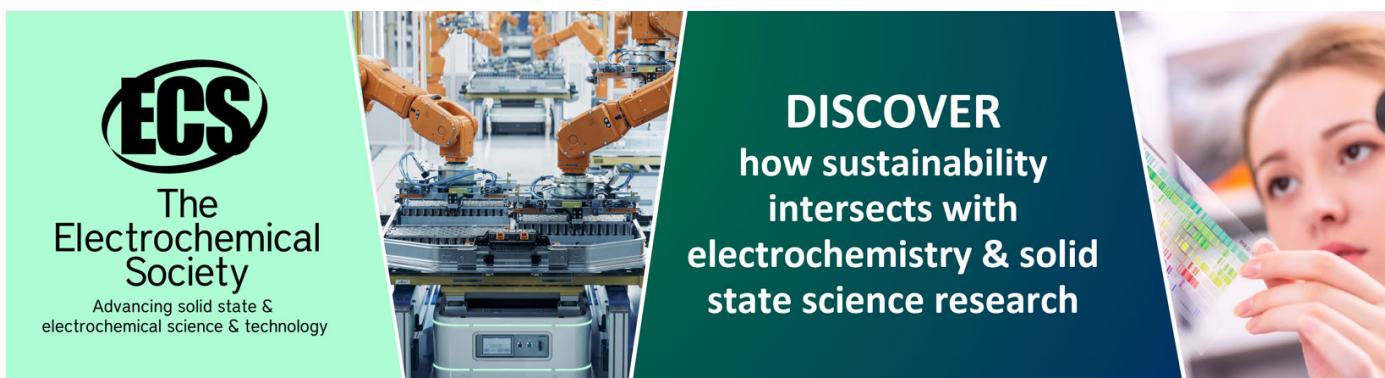
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Research on Formation Pressure Monitoring While Drilling in Deep Water with High Temperature and High Pressure Wells

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Abstract. With the deepening of deep water with HTHP oil and gas exploration, there are various reservoir systems, which are complex pressure systems and high and low pressure interfacing in the strata drilled at present. Downhole complications occur frequently in the drilling process, which seriously affects the safety of drilling operations. In this paper, we combine with the drilling example of deep water HTHP X1 well, dc index method and rock strength method are used to monitor formation pressure while drilling. The results show that the rock strength method is more accurate for pressure monitoring of deep water HTHP wells, and it can provide a reference for subsequent monitoring of formation pressure of deep water HTHP wells.

1. Introduction

Deep-water HTHP wells have the characteristics of high drilling risk, high price, and long consumption time. Drilling process has great difficulties in deep-water areas. When the surrounding environment is abnormal, it may cause accidents such as kicks, well leakage and blowouts [1]. The formation pressure measurement method before drilling relies on the acoustic velocity caused by artificial earthquakes and the geological conditions of the surrounding areas. Due to the poor detection accuracy of acoustic wave velocity caused by earthquake and the diversity of surrounding geological conditions, the accuracy of formation pressure detection completed before drilling in deep water HTHP well is very low, and it's not easy to calculate the accurate formation pressure. The detection of formation pressure while drilling [2] plays an important role in the drilling process of deep water HTHP wells, and it is the foundation for ensuring safe and efficient drilling. In the drilling operation, formation pressure obtained by recording drilling data and other drilling information [3].

The main principle is to calculate formation pressure deviation according to actual pressure and deviation trend from normal pressure line through the interaction relationship between mudstones in geology. At the same time, the overall pressure evaluation is completed according to the common parameters, gas, mudstone characteristics and information collection characteristics in drilling operations. And based on the evaluation results, the differences between formation pressures are analyzed. The commonly used methods for detecting formation pressure under current conditions are calculated based on the dc index method [4], the Eaton method [5-7], the Sigma index method [8], the rock strength method [9], the geothermal gradient method [10] and so on. In this paper, the dc index



method and the rock strength method are used to carry out the formation pressure monitoring of deep water HTHP wells, and the applicability of the two methods in deep water HTHP area is analysed and compared.

2. Calculation of formation pressure by dc index method

2.1. Dc index method calculation model

The dc index method take into account the effect of compaction and the differential pressure of the well on the rate of penetration. The normal compacted strata of mud shale, with the increase of buried depth, the formation pressure is increased by the overburden pressure, the porosity is gradually decreasing, and the rock becomes denser and denser, which causes the ROP to decrease and the dc index gradually increases. At the same time, the influence of parameters such as ROP, bit size and drilling fluid performance should be considered. It is necessary to correct the formation pressure calculation model in the calculation process.

$$d_c = \frac{\lg\left(\frac{R}{60N}\right) \rho_n}{\lg\left(\frac{12W}{10^6 B}\right) \rho_m} \quad (1)$$

By standardizing the parameters in the formula, the formula can become:

$$d_c = \frac{\lg\left(\frac{3.282}{NT}\right) \rho_n}{\lg\left(\frac{0.0684W}{D}\right) \rho_m} \quad (2)$$

In the formula: N is the rotational speed, the unit is r/min; T is the time consumed by drilling, the unit is min/m; W is the pressure detected during drilling, the unit is kN; D is the diameter of the drill bit, the unit is mm; m is the density of the solution detected during actual drilling, the unit is g/cm³; n is the equivalent density of the formation, the unit is g/cm³.

2.2. Build dc index trend based on normal compaction

Due to the compaction difference of strata in different regions, the compaction laws are different, so there are different models for the normal compaction trend line. They are maybe exponential, logarithmic or polynomial[11,12], etc. It is necessary to select the appropriate compaction trend line and regional index according to the geological conditions of the drilled area. Using the dc index method to build up a normal compaction trend line, the data of the drilling while logging of a continuous shale is usually selected to obtain the dc index value. The trend line is established by analyzing the scatter, lithology, drilling parameters, and drilling fluid during the drilling period. In this paper, the normal compaction trend line adopts the exponential type, and its formula is:

$$d_c = ae^{bH} \quad (3)$$

Taking the logarithmic form for formula (3):

$$\ln dc = bH + \ln a \quad (4)$$

In the formula (4): H is the depth of the well, m; b is the slope; a is the intercept.

According to the deviation between the dc index value obtained by the logging and the shale compaction trend line, the compaction condition of the formation can be qualitatively judged. If the measured value is left deviation from the normal trend, it indicates that the formation is under-compacted and belongs to abnormal high pressure, and if the right deviation indicates that the formation pressure is abnormal low pressure.

2.3. The formation pressure calculation model

After establishing the normal compaction trend line, the equivalent depth method, Eaton method and ratio method can be selected to calculate the formation pressure model. The Eaton method has the best adaptability and is the most widely used pressure calculation method, and the error can be controlled within a certain reasonable range. Therefore, the Eaton method is usually used to calculate the formation pore pressure in logging while drilling. The Eaton calculation formula is:

$$\rho_p = \rho_o - (\rho_o - \rho_n) \left(\frac{d_c}{d_{cn}} \right)^n \quad (5)$$

After considering the influence of the parameters such as the drilling pressure, the bit size and the drilling fluid performance on the ROP, the formation pressure calculation model needs to be corrected.

$$\rho_p = \rho_o - (\rho_o - \rho_n) \left(\frac{d_c}{d_{cn}} \right)^n \quad (6)$$

In the formula(6): ρ_p is formation pressure equivalent density, g/cm³; ρ_n is normal formation pressure equivalent density, g/cm³; ρ_o is overlying pressure equivalent density, g/cm³; n is Eaton coefficient, a is correction coefficient.

3. Rock strength method to calculate the formation pressure

3.1. Introduction of rock strength method

Judging the formation pressure value based on the rock strength is the commonly used formation pressure while drilling detection method. In the drilling operation, the drill bit will penetrate to the rock. This phenomenon is mostly caused by the surrounding rock and the gap between the holes. And the drilling process is modeled by above phenomenon, and we can obtain the relationship between the formation pressure and the rock strength.

3.2. Construction of rock anti-drilling strength model

The degree of drilling resistance of surrounding rocks is the anti-interference ability of rocks in drilling operations. The formula is:

$$S_R = \alpha f_1(W) f_2(N) f_3(R) f_4(D) \times f_5(E_b) f_6(B_i) f_7(L) f_8(\Delta p) f_9(Q) \quad (7)$$

In the formula, α it is a constant; W represents the drilling weight during the drilling process, kN; N is the rotation speed of drilling bit, r/min; R is the ROP, m/h; D is the diameter of the bit, mm; L is the rock property of the formation; Δp is the pressure difference, MPa; Q is the displacement of drilling fluid, L/s, and E_b is the wear factor.

Through simulation, formula (7) can be further simplified as follows:

$$S_R = \alpha \frac{WN}{R(B_D)^{r_3}} (E_b)^{r_1} \left[\frac{Q}{B_D D_n} \right]^{r_2} f(t) \quad (8)$$

$$f(t) = \frac{(N_i)^{\beta r_4}}{200} e^{\partial T} \quad (9)$$

In the formula (9): E_b is the rotation index in the drilling process; r_1 , r_2 , r_3 , r_4 , ∂ are constant.

3.3. Establishment of rock anti-drilling strength and bottom hole pressure differential model

After obtaining the relevant data and other information of the actual drilling process, the rock strength and the corresponding bottom hole pressure difference are calculated, and the data fitting analysis is carried out to obtain the following model:

$$\Delta p = a_2 \tan[\pi(S_{AR}/S_{RO})/(S_{Rmax}/S_{RO}) - c_2] + d_2 \quad (10)$$

In the formula (10): α_2 、 c_2 、 d_2 are constant; S_{RO} is the rock strength when the bottom hole pressure difference is zero, MPa; S_{AR} is the average rock strength, MPa; S_{Rmax} is the maximum rock strength of shale under the condition of overbalanced drilling process, MPa.

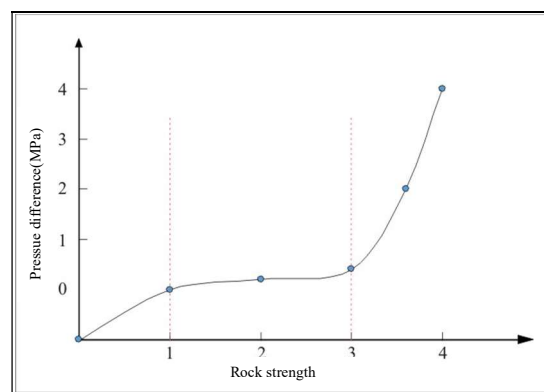


Figure 1. Relation diagram between bottom-hole pressure difference and rock strength.

Figure 1. is a specific expression of the formula (10), which characterizes the interaction between the pressure difference at the well bottom and the rock strength. This model is mostly based on the characteristics of undercompaction diagenesis. The main characteristics of this model are: firstly, similar exponential curves are shown due to the positive pressure difference of the model, which has been verified in the previous logging while drilling process. Secondly, when the ΔP value is large, the rock can withstand the maximum strength, which is also obtained from previous laboratory experiments based on triaxial method. Finally, when drilling under unbalanced conditions, the slight difference will lead to great changes in rock strength, because this model can detect formation pressure under abnormal conditions sensitively.

3.4. Formation Pore Pressure Calculation

Quantitative evaluation of the pressure between formation voids is made by the pressure difference at the bottom of the well. The formula is :

$$P_p = P_n - \Delta p \quad (11)$$

In the formula, P_p is the formation pressure, MPa; P_n is the bottom hole pressure of drilling fluid, MPa.

4. Field application

Well X1 is a HTHP exploration well in the South China Sea. The water depth of this well is 1006 m, well depth is 4100 m and bottom hole temperature is 187 C. The formation pressure coefficient near the target formation ranges from 2.17 to 2.25. Based on the calculation method of dc index and the rock strength, the formation pressure while drilling in X1 well is tested, and then the correlation analysis with the recorded data is carried out, the results is shown in Table 1. This phenomenon shows that when the

accuracy of dc index calculation is more than 90%, the detection accuracy based on rock strength calculation is more than 95%. Figure 2. is a cross-section of measured results obtained by two methods in Well X1.

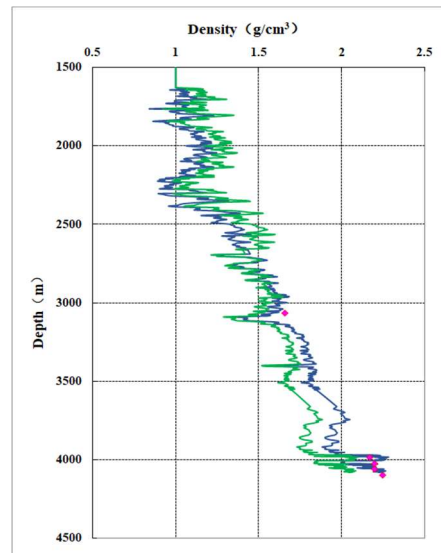


Figure 2. Comparative section of monitoring results of well X1 with two methods.

Table 1. Comparison table of pore pressure gradient values monitored by rock strength method and dc index method with measured values.

Well name	Well depth	Measured pressure density (g/cm ³)	Rock strength method		Dc index method	
			Pressrue density (g/cm ³)	errors	Pressrue density (g/cm ³)	errors
X1	3065	1.66	1.58	4.8	1.51	1.0
	3987	2.17	2.25	4.7	2.02	6.9
	4023	2.2	2.02	8.2	1.86	5.5
	4057	2.2	2.21	0.5	2.04	7.3
	4098	2.25	2.23	0.9	2.06	8.5

5. Conclusions and Suggestions

(1) The results of X1 show that the error of while-drilling detection obtained by dc exponential method is less than 10% and that by rock strength method is less than 5%. This shows that more accurate detection can be obtained based on rock strength method, which can be improved by timely and accurate detection of formation pressure change for subsequent deep-water high temperature and high pressure operation.

(2) Based on rock strength method, the defects of dc index method are solved in practical calculation. After analyzing the types of drill bits, drilling conditions and changes of hydraulic parameters in actual drilling, there is no need to carry out artificial interference caused by pressure trend.

(3) The establishment of rock strength and formation pressure models is inseparable from the characteristics of rocks. This process is not related to the rock properties under high temperature and high pressure conditions, so it has a wider application range than the dc index method.

Acknowledgments

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