Research and application of borehole structure optimization based on pre-drill risk assessment

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Abstract: Borehole structure design based on pre-drill risk assessment and considering risks related to drilling operation is the pre-condition for safe and smooth drilling operation. Major risks of drilling operation include lost circulation, blowout, sidewall collapsing, sticking and failure of drilling tools etc. In the study, studying data from neighboring wells was used to calculate the profile of formation pressure with credibility in the target well, then the borehole structure design for the target well assessment by using the drilling risk assessment to predict engineering risks before drilling. Finally, the prediction results were used to optimize borehole structure design to prevent such drilling risks. The newly-developed technique provides a scientific basis for lowering probability and frequency of drilling engineering risks, and shortening time required to drill a well, which is of great significance for safe and high-efficient drilling.

1. Introduction

With the deep and complex formation oil and gas exploitation, more and more high requirement to drilling technology. Because of the complexity of reservoir buried depth, rock mass environment, deep well complex formation often appear all sorts of underground complex and the accident in the process of drilling, Drilling engineering risk problem became the restriction bottleneck of deep well complex formation technology implementation. Casing program design is one of the most important content of drilling engineering design, it is up to avoid risks, ensure the safety of drilling engineering and high efficiency. Well bore structure design has experienced three main stages. From 1900s to the late 1960s, belongs to the experience accumulation stage, determine the basic structure of a three-stage, formed the size of API standard, put forward to satisfy the engineering will seal condition of well bore structure design. In the late 1960s to the 1980s, the theory of developed, put forward the bottom-up, top-down, and both of them combined design method, realized the quantification method of well bore structure design. In the late 1980s, in order to solve the problems of the deep well complex formation, well bore structure optimization design gradually developed to the direction of system engineering.

The author puts forward a set of based on risk prediction before drilling, a new method for the optimization of well bore structure for deep well complex formation of well bore structure optimization problem, using the drilling risk assessment methods, treatment of drill goal well evaluate the design of a set of well bore structure, get to drill the target well in real risk may occur in the process of drilling, design and optimization of well bore structure based on forecast results, avoid the happening of the
drilling risk at the design stage, finally the author gives a set of well bore structure of drilling risk minimization scheme, the drilling risk control at the lowest level of probability.

1.1. Pre-drill prediction of formation pressure with credibility

The formation pore pressure, fracture pressure and collapse pressure profile are the important basis of well bore structure design\(^{12-13}\). But the complexity of the deep well complex oil and gas geological stratum, explain the incomplete information, and the precision of the mathematical model. It is impossible to get the true value of formation pressure, the error is objective existence. Therefore, formation pressure prediction result is uncertain, the true value will be in the form of a certain probability distribution in a certain range. Petroleum university GUAN Zhichuan put forward the concept of containing credibility formation pressure profile\(^{14-15}\). Forecasting results of this method is no longer a single value, but has a credibility interval. This interval distribution in the form of a more practical for engineering personnel to make it better able to grasp the formation pressure is helpful to reduce drilling accidents.

Pre-drill, which combined with Eaton method and Fillippone, calculated credibility of formation pore pressure. According to the seismic interval velocity data, the main progress divided into two steps, First, according to the seismic interval velocity, using Fillippone formation pressure prediction methods, calculate the single value formation pressure of the whole section. Secondly, obtain the formation pressure in back Eaton method formula index \(n\) value. Then, we can determine the interval numerical probability distribution form of Eaton index. At last, we will contain some kind of probability distribution in Eaton Eaton index method to calculate formation pressure distribution containing credibility. The specific calculation process is shown in figure 1.

Stratum rupture and collapse pressure in the research of most scholars are regarded as the study content of borehole wall stability accurately predicting strata collapse pressure and fracture is of great significance for the risk early warning. Pre-drilling calculating the credibility stratum rupture and collapse pressure mainly divided into four steps. First, similar structure selection, according to the geophysical exploration departments provide information of geological structure and formation lithology interpretation seek for wells near the target with similar structure has drilling, doing comparison and analysis between the layers, seeking higher similarity of Wells. Secondly, based on the similar structure of well logging data, core indoor experiment and Log data, each bite similar structure well in tectonic stress coefficient, then to probability and statistics analysis, the coefficient of distribution and status of its value would be obtained. According to the similar structure of well data, established the relevant rock mechanics parameter model, applied to the interval velocity data of well drilling targets the determination of rock mechanics parameters, the results of rock mechanics parameters is no longer a single value, but the range of a distribution form. Finally, worked out with probability distribution information of each rock mechanics parameters and tectonic stress coefficient into formation collapse and fracture pressure calculation formula, calculate the formation collapse and fracture pressure containing credibility.

The specific calculation process is shown in figure 2.
Fig. 1 Work flow of calculating formation pore pressure with credibility before drilling

In the type: $G_P$—The formation pore pressure gradient
$G_0$—The pressure gradient in the overlying strata
$G_h$—Normal hydrostatic pressure gradient
$V_{int}$—Normal hydrostatic pressure gradient
$V_n$—Normal compaction acoustic velocity

$G_P = \frac{V_{max}-V_{int}}{V_{max}-V_{min}} G_0$

$n = \ln \frac{G_0-G_P}{G_0-G_h} / \ln \frac{V_{int}}{V_n}$

$G_P = G_0 - (G_0 - G_h) \ln \frac{V_{int}}{V_n}$

Fig. 2 Work flow of calculating fracturing and collapsing pressure with credibility before drilling

Through these steps, we could calculate formation collapse and fracture pressure value range, it is concluded that the collapse and fracture pressure is no longer a single curve, but a range of a distribution forms. Finally it is concluded that the credible information to collapse and fracture pressure profile. It contained the credibility of formation pore pressure profile similar to the establishment of the method. Select 5 wells in Niudong block of Qinghai oilfield (Niu-1, Niu-2, Niu-101, Niu1-2-10,
Niu-102), the 5 Wells are all vertical Wells. Assuming Niu-102 will be drilled soon, the other 4 wells have been drilled for similar structure. In accordance with the above methods, calculate the target well drilling formation pressure profile containing credibility, after considering wellbore structure design for drill goal well pressure constraints, containing the credibility of as shown in figure 3.

Fig. 3 Pressure constraints and extent of pressure uncertainty in the target well

### 1.2. Prediction and assessment methods of drilling risks

Based on design constraints of safe drilling fluid density, the author mainly divides into the risk of casing under level and deep kick in drilling process, lost circulation, hole collapse, four categories of differential pressure sticking. This paper expounds the types of drilling engineering risks, mainly to formation pressure profile and safe drilling fluid density constraint condition as the foundation, and the reasons of the risk is also safe drilling fluid density constraint conditions are not met. For special formation and other reasons caused by the above or other complex situation, under the casing layer and deep design, special treatment should be based on concrete layer, established geological will point, made a backup plan, reduced the occurrence of downhole complicated conditions in the process of drilling.

Defined four drilling project risk evaluation models, as shown in table 1.

**Table 1 Model of four drilling risks**

| Risk categories          | risk models                                                                 |
|--------------------------|----------------------------------------------------------------------------|
| well kick                | $R_{w} = P(\rho_{f} < \rho_{a}) = 1 - F_{\rho_{w}}(\rho_{a})$               |
| leakage                  | $R_{l} = P(\rho_{f} > \rho_{a}) = F_{\rho_{l}}(\rho_{a})$                    |
| hole-wall collapsing      | $R_{h} = \max[P(\rho_{f} < \rho_{a}) , P(\rho_{f} > \rho_{a})]$ = max $[1 - F_{\rho_{h}}(\rho_{a}) , F_{\rho_{h}}(\rho_{a})]$ |
| Differential pressure sticking | $R_{i} = P(\rho_{f} > \rho_{a}) = F_{\rho_{i}}(\rho_{a})$ |
In the table, $R_{k,h}$, $R_{l,h}$, $R_{c,h}$, $R_{sk,h}$ denoting the risk probability of wellbore, well leakage, hole wall collapse and differential pressure card.

$\rho_{k,h}$, $\rho_{l,h}$, $\rho_{c,h}$, $\rho_{sk,h}$ Respectively well depth $h$ place kick lower limit value of drilling fluid density, lost circulation prevention upper limit of drilling fluid density, hole collapse upper and lower limit value of drilling fluid density, the differential pressure sticking lower limit value of drilling fluid density: $\rho_{d,h}$ represented well depth $h$ drilling fluid density.

For example, Kick risk representatives depth $h$ place the drilling fluid density less than that in control kick probability value of the lower limit value of drilling fluid density $\rho_{k,h}$ ($\rho_{d}<\rho_{k,h}$). According to the probability theory, as shown in figure 4, $P_{k,h}(\rho)$ is prevent kick lower limit value of drilling fluid density distribution of probability density function, so the drilling fluid density is less than the kick lower limit value of drilling fluid density probability $P(<)$ is the area of the shaded part in figure 4. It is the $1-F_{\rho_{k,h}}(\rho)$ that prevent kick cumulative probability distribution function of the upper limit value of drilling fluid density, the number of $F_{\rho_{k,h}}(\rho)$ is prevented kick lower limit value of drilling fluid density equaled to the cumulative probability when drilling fluid density. Other risk models are the probability of the basic theory and kick the same risk.

Fig. 4 Probability density and cumulative probability density function of lower limits of kick-proof drilling fluid density

According to the risk evaluation model, the target well’s risk evaluation on the design of a set of well bore structure will be calculated by the several common downhole accidents throughout the depth of the hole of risk distribution and probability value. The equivalent value is drilling fluid density.

For drilling targets Niu-102 for instance, we can get risk assessment (Table 2). According to drilling target of well casing program design, we can analyze the well history data. Sorting have actually occurred in the process of drilling downhole complex and accident, as shown in table 3.

Table 2 Borehole structure design of the target well

| Casing            | Well depth /m | Drilling fluid density / g.cm$^{-3}$ |
|-------------------|---------------|-------------------------------------|
| Surface casing    | 403           | 1.08-1.12                           |
| intermediate casing| 2000          | 1.20-1.80                           |
| oil-string casing | 3487          | 1.47-1.60                           |

Table 3 Actual downhole complications and incidents of the target well

| Well depth /m | Downhole complex and accident     |
|---------------|-----------------------------------|
| 1185          | overflow                          |
| 1208          | well kick                         |
| 1850          | casing overflow occurs            |
| 1955          | borehole collapse                 |
| 2058          | collapse                          |

Using drilling engineering risk evaluation method for risk analysis of well bore structure, the results are shown in figure 5. As can be seen from the figure, the degree of risk assessment and risk types of
downhole mainly is kick and hole collapse. The kick will occurred from 1100 to 1200 meter-degree and from 1800 to 2000 meter-degree, the hole collapse risk zone is located from 1800 to 2000 meter-degree. Compared to the actual well drilling engineering risk (table 3), drilling engineering risk prediction was consistent with the actual downhole complex and accident. Through the drilling Risk prediction project, the drilling target of well casing program design cannot ensure the security of drilling construction, we need further optimization and adjustment of well bore structure design.

Fig. 5 Drilling engineering risk prediction results (with drilling fluid density of 1.5 g/cm$^3$ at the first spud-in)

2. Case study

Well bore structure in drilling engineering risk includes two aspects, drilling fluid density and casing level and deep. Assume that don't change the casing layers of well bore structure and deep, by changing the drilling fluid density to avoid the risk of drilling engineering.

Through the figure 5 drilling engineering risk prediction results can be seen, the intermediate casing stage risk kick higher, 1100 to 1200 meter-degree interval place kick risk rate is up to 98%. Analysis of it reasons, risk is largely due to the interval of drilling fluid density is less than the kick density lower limit, so you should improve the density of drilling fluid. Accordingly, as the two schemes will control of drilling fluid density at around 1.5 g/cm$^3$. Risk analysis was carried out on the adjustment of well bore structure scheme, the results are shown in figure 6, 1100 to 1200 meter-degree interval place kick well to avoid risk, but from 1800 to 2000 meter-degree interval, appeared a kick and hole collapse risk at the same time, among them the biggest kick risk probability is 100%, hole collapse risk of maximum probability is 80%. Through further analysis of underground insurance mechanism, the main reason of the drilling fluid density is too low, it can't rise to balance the action of borehole pressure and supporting wall, avoid the two types of risk measures approximately the same. Due to the same interval, we can adopt the same adjustment scheme to avoid. In order to circumvent the two risks, will open the third spud of drilling fluid density to 1.6 g/cm$^3$, the adjusted risk assessment results of drilling fluid density is shown in figure 7.
Comprehensive figures 6, 7, the risk assessment results, we can conclude the second spud drilling fluid density, to circumvent from 1100 to 1200 meter-degree interval place kick the happening of the risk. By adjusting the third spud drilling fluid density, the risk of wellbore at the Wells from 1800 to 2000 meter-degree well and the risk of collapse of the wellbore have been circumvented, but due to the improvement of the drilling fluid density, the risk of pressure differential card is also found from 2100 to 2500 meter-degree well, and the risk layer is more longer than the other.

Above all, the goal to drill Well Niu-102-Well, only by adjusting the density of drilling fluid level without changing the casing and the deep, can’t effectively avoid the risk of drilling engineering. Risk
analysis results show that the above needs by changing the casing level and deep to circumvent the risk of drilling engineering. Well bore structure design method based on containing credibility and risk minimization principle, the treatment of well drilling targets cattle 102 well bore structure optimization design, scheme are shown in table 4.

Table 4 Recommended design optimization for borehole structure of the target well

| Casing          | Well depth /m | Drilling fluid density / g.cm\(^{-3}\) |
|-----------------|---------------|----------------------------------------|
| Surface casing  | 403           | 1.2                                    |
| intermediate casing | 2000          | 1.6                                    |
| oil-string casing | 3487          | 1.5                                    |

The technology of casing under deeply from 1798 to 2000 meter-degree and the second spud drilling fluid density of 1.6 g/cm\(^3\), ensure the safety of around 2000 meter-degree narrow hole drilling fluid density window of safe drilling. At the same time, the recommended for risk assessment, the results are shown in figure 8.

Fig. 8 Recommended design optimization for borehole structure of the target well and predicted drilling risks

Through risk analysis we can be seen that the recommended scheme of drilling engineering risk assessment results show that the well kick in drilling process, lost circulation, borehole wall collapse and differential pressure sticking the probability of occurrence of a risk is almost zero. It showed that the set of solutions to control the drilling engineering risk the possibility of lowest degree, can satisfy the safety drilling requirements.

Conclusion based on the risk prediction before drilling of well bore structure optimization method, the specific process as shown in figure 9.
3 Conclusions

According to the drilling risk quantitative evaluation method, established a well full of hole drilling risk probability curve, we can get leakage, spray, collapse, card project risk happened such as well depth position size and risk. With the actual drilling process of downhole complex situation, both of them have good alignment.

Risk prediction before drilling and the combination of well bore structure optimization, was proposed based on risk prediction before drilling, a new method for the optimization of well bore structure in drilling construction of reasonable avoid project risk and adjust the construction plan, safe and fast drilling provides the scientific basis, can effectively reduce the project risk accident probability and frequency, shorten the construction cycle, was great significance for the safe and efficient drilling construction.

Choice similar structure well accurately predicted before drilling for drilling target well pressure profile is very important, the basis of adjacent well formation pressure, space position, target area space continuity was the key factor that influence selection of similar structure wells. For fault or geological structure was complicated, need to fully grasp the geological structure characteristics, and seismic data structure, made a similar structure partition field, as far as possible to get more accurate information for drilling pressure.
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