Improving drilling speed and borehole quality in ultra-deep complex formations through rock mechanics research

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Abstract. Halahatang oilfield in Tarim Basin is a typical ultra deep fractured vuggy carbonate reservoir, which is the main production area of crude oil in Tarim Basin. The wellbore instability is serious in Triassic and lower strata (the borehole enlargement rate is 22\% - 31\%). Due to the complex rock characteristics, the drilling cycle for single well is long (124 days on average), and it is difficult to speed up. Based on the log interpretation curves, the calculation methods of pore pressure, collapse pressure and fracture pressure profiles established, and the spatial distribution characteristics of three pressures in this area were analysed; The rock drillability, rock hardness, compressive strength and abrasiveness of the roller bit and PDC bit single well measured by laboratory tests. Based on the statistical regression method, the relationship between the above drilling rock mechanical parameters and logging acoustic time difference and the formation drillability profile single were studied. The research results guide the drilling design optimization and operation of 15 wells in Ha 8 and Ha 12 blocks, The average drilling cycle is reduced by 21\% (from 124 days to 98 days), and the hole enlargement rate is reduced from 24\% to less than 10\%.

1. Introduction
Halahatang oilfield is the main oil producing area in Tarim Basin, China. Drilling practice shows that in this area, borehole enlargement and borehole collapse are common, and the borehole enlargement is more than 20\%, especially in the Triassic system. Borehole instability can leads to logging obstruction, sticking and other drilling complications\cite{1-3}. In addition, due to the complex rock characteristics in this area, the single well drilling cycle is long (average 124 days), and it is difficult to increase the drilling speed. Therefore, this paper establishes three pressure calculation and formation drillability evaluation methods in this area by combining indoor test, mathematical statistics analysis and numerical simulation, to guide the safe and rapid drilling in the area.

2. Fine description of safe drilling fluid density window

2.1. In situ stress evaluation
The fracturing data curve obtained by hydraulic fracturing can be divided into complete fracturing curve and non-complete fracturing curve (Figure 1). Through the research, the method of interpretation of in-situ stress by complete fracturing curve and non-complete fracturing curve could be established, referring to Eq1-5 for details\cite{4}.
In formulas, $P_f$ — fracturing pressure; $P_p$ — pore pressure; $S_t$ — tensile strength; $P_{pro}$ — fracture propagation pressure; $\alpha$ — Biot coefficient; $\Delta P$ — pressure loss.

The in-situ stress was interpreted by using the field test data in Halahatang area, and the interpretation results are shown in Table 1.

Table 1. Formatting sections, subsections and subsubsections.

| Well | Depth | Formation | $P_f$ Mpa | $P_p$ Mpa | $S_t$ Mpa | $\sigma_h$ Mpa | $\sigma_v$ Mpa | $\sigma_h$ Mpa |
|------|-------|-----------|-----------|-----------|-----------|---------------|---------------|---------------|
| Ha1  | 1450.09 | N2K       | 40.84     | 35.44     | 6.01      | 56.02         | 36.19         | 39.75         |
| Ha1  | 4548.15 | J         | 81.32     | 42.45     | 7.51      | 106.19        | 67.08         | 74.66         |
| Ha1  | 5863   | C         | 86.22     | 60.48     | 8.92      | 97.75         | 68.43         | 96.05         |
| Ha2  | 4398.78 | J         | 73.93     | 47.61     | 7.73      | 90.10         | 60.03         | 71.62         |
| Ha4  | 1477.34 | N2K       | 31.59     | 31.71     | 5.99      | 36.96         | 26.14         | 28.96         |
| Ha4  | 4674.7 | K         | 77.03     | 49.53     | 7.68      | 91.84         | 61.99         | 73.14         |
| Ha5  | 4000   | K         | 68.26     | 36.78     | 6.83      | 85.87         | 55.23         | 64.62         |
| Ha6  | 1807.25 | N2K       | 30.03     | 35.61     | 6.62      | 29.61         | 23.61         | 27.53         |
| Ha6  | 5400   | P         | 78.86     | 59.45     | 8.74      | 82.47         | 60.77         | 71.14         |
| Ha6  | 6588   | Q         | 80.8      | 64.98     | 9.12      | 77.74         | 60.64         | 68.15         |
| Ha7  | 1504.21 | N         | 26.77     | 31.24     | 5.69      | 26.86         | 21.19         | 24.33         |
| Ha7  | 5060   | T         | 87.04     | 61.45     | 8.35      | 103.08        | 70.83         | 89.62         |
| Ha8  | 1504   | N2K       | 27.12     | 29.47     | 6.21      | 28.88         | 21.51         | 26.53         |
| Ha8  | 5307.92 | T         | 91.19     | 63.21     | 8.26      | 106.97        | 73.84         | 86.51         |
| Ha11 | 1499.75 | N2k       | 27.91     | 30.62     | 5.94      | 29.53         | 22.27         | 26.58         |
According to the method of interpreting rock mechanics parameters based on logging data, the cohesion, internal friction angle and tensile strength of formation such as N2k, J, C, K, P, Q, N and T can be obtained respectively (Table 2), which provides the basis for collapse pressure model parameters based on molcoulomb criterion\(^5\)\(^8\). Through analysis, it is found that the cohesion of N2k formation is smaller than other strata (6.35-11.89MPa), and the cohesion of formation T is larger. The average cohesion, internal friction angle, tensile strength in Halahatang area are 20.43MPa, 40.1°, 60.65MPa respectively (Table 2).

**Table 2. Evaluation results of rock mechanics parameters**

| Well | Depth/m | Formation | Cohesion/MPa | Internal friction/° | Tensile/MPa |
|------|---------|-----------|--------------|---------------------|-------------|
| Ha1  | 1450.09 | N2K       | 7.62         | 35.74               | 3.62        |
| Ha1  | 4548.15 | J         | 28.81        | 42.48               | 7.82        |
| Ha1  | 5863    | C         | 29.61        | 45.37               | 9.11        |
| Ha2  | 4398.78 | J         | 27.86        | 41.10               | 7.52        |
| Ha4  | 1477.34 | N2K       | 6.97         | 38.04               | 4.61        |
| Ha4  | 4674.7  | K         | 27.55        | 43.31               | 7.63        |
| Ha5  | 4000    | K         | 24.70        | 39.18               | 5.02        |
| Ha6  | 1807.25 | N2K       | 7.22         | 36.89               | 4.11        |
| Ha6  | 5400    | P         | 31.20        | 40.62               | 9.17        |
| Ha6  | 6588    | Q         | 30.90        | 38.47               | 8.17        |
| Ha7  | 1504.21 | N         | 6.81         | 36.04               | 5.62        |
| Ha7  | 5060    | T         | 30.02        | 46.74               | 8.75        |
| Ha8  | 1504    | N2K       | 6.35         | 38.71               | 5.13        |
| Ha8  | 5307.92 | T         | 28.95        | 42.67               | 8.79        |
| Ha11 | 1499.75 | N2k       | 11.89        | 36.09               | 4.66        |

The tectonic stress coefficient of Halahatang area can be obtained by comparing and analyzing the in-situ stress interpreted by fracturing curve with the in-situ stress obtained by logging method. The tertiary, Cretaceous, Jurassic and Triassic in Halahatang area are selected in the later in-situ stress calculation \(\xi_1=0.00012, \xi_2=0.0004\) in Carboniferous and Ordovician \(\xi_1=0.00015, \xi_2=0.0005\). The in-situ stresses of Neogene Kuqa formation, Paleogene, Cretaceous Bashijiqike formation and Permian are interpolated to study the spatial distribution characteristics of vertical stress, maximum horizontal principal stress and minimum horizontal principal stress. Through the analysis, it is found that the in-situ stress state in Halahatang area is vertical stress > maximum horizontal principal in-situ stress > minimum horizontal principal in-situ stress, and the vertical stress range is 2.30 ~ 2.62. The vertical stress of Permian strata and Cretaceous Bashijiqike formation and below is high (2.45-2.62), and the maximum horizontal principal stress range is 1.65-2.0. In addition to the low value area in the southwest of Permian strata, the other three formations have high values in the southwest direction, and the minimum horizontal principal stress (1.4-1.72) is characterized by high values in the southwest and northeast.

![In situ stress distribution of Neogene Kuqa formation](image-url)
2.2. Establishment of three pressure profile

2.2.1. Pore Pressure. There is no mature method to determine the formation pore pressure of non-mudstone or sandy mudstone formation at home and abroad, but the target formation in Halahatang area is mainly limestone formation and a small amount of carbonate formation. Through the comprehensive analysis of the geological structure and lithology of the local formation, and then comparing the trial results of different pressure calculation methods, the most reasonable and accurate prediction method is finally found, that is, the pore pressure profile established by Eaton method based on the normal compaction theory. After repeated trial calculation and analysis, and referring to the geological stratification and field well history data, different trend line division methods were adopted for different well areas in Halahatang area, and the trend lines of the two areas were determined. The specific data are shown in Table 3:

| Block                  | intercept    | Slope        | Eaton Index |
|------------------------|--------------|--------------|-------------|
| Halahatang (Three sections) | 2.149801     | -0.000728    | 2.6         |
|                        | 2.153183     | -0.000535    | 2.6         |
|                        | 1.569812     | 0.000482     | 2.6         |
|                        | 2.20621      | -0.0001415   | 2.6         |
| Halahatang (Four sections) | 2.10586     | -0.0000609   | 2.6         |
|                        | 2.18944      | -0.0000646   | 2.6         |
|                        | 1.77496      | 0.0000055    | 2.6         |
2.3. Calculation of collapse pressure and rupture pressure

Based on the in-situ stress analysis and pore pressure settlement results, the collapse pressure profile was established based on the Mohr-Coulomb criterion, and the fracture pressure calculation refers to the three pressure evaluation method. By linear interpolation, the spatial distribution characteristics of the three pressures in Halahatang area were further analysed.

The regional distribution characteristics of the three pressures in Halahatang area are as follows:

- The equivalent density of fracture pressure ranges from 1.65 to 1.82. The distribution characteristics of plane range are that the high value area is near the central well Ha10, Ha6 and Ha12 in the north and around the eastern well Ha9, and the low value area is near the well Ha4 and well Ha5 in the southwest. The equivalent drilling fluid density is about 1.4 ~ 1.5.
- The equivalent density of pore pressure ranges from 1.05 to 1.25. The distribution characteristics of the plane area are two low value points centered on well Ha6 and well Ha9 in the central and southern part, with the value range of 1.05 ~ 1.1; the high value points centered on well Ha11 and well Ha12 in the northwest and the local area centered on well Ha2 in the East have abnormal pressure points, with the equivalent mud density value of 1.23 ~ 1.25.
- The equivalent mud density of collapse pressure is between 0.85 and 1.20. The overall distribution of the area is X-shaped: in the middle of the horizontal, the low value zone is centered on well Ha12, well Ha7, well Ha6, well Ha1 and well Ha9, and the high value points on the left and right sides are centered on well Ha13 and well Ha2, showing a high value distribution, with the value range of 1.15 ~ 1.26.

2.4. Three pressure interpretation accuracy demonstration

By comparing the calculated results of three pressure profiles with the actual interpretation results, the following conclusions can be drawn:

- Through the analysis of the detection results of three pressure single wells in Halahatang area and the actual interpretation results, it is found that the interpretation accuracy of pore pressure is generally more than 95%, and the error of a few (1 ~ 2 points) detection results is about 4.5%;
- Similar to the calculation result of in-situ stress profile, there is a systematic error between the detection result and the interpretation result of actual fracturing, which can be corrected in the later stage, which can provide the basis for the final systematic correction of the detection result. The systematic error shows that the calculated results are generally about 2% larger than the actual interpretation results.

2.5. Determination of safety density window

By comparing the characteristics of in-situ stress distribution and three pressures of several real drilling wells with relatively complete data, it is concluded that: the overall in-situ stress in Halahatang area presents a capital X-type difference distribution, ha10 well area is located at the intersection of X, the in-situ stress and three pressures at the north and south ends are generally higher, and the in-situ stress and three pressures at the East and west sides are smaller.

Based on the regional differences in the above analysis results, the safe mud density window can be divided into four areas, namely, block Ha8-Ha12-Ha10, block Ha16-Ha15, block Ha13-Ha6-Ha601-Ha9, block ha5-ha11, block Ha7-Ha701-Ha2.
3. Study on the evaluation of drillability of block formation

In order to find out the internal relation between the mechanical parameters of rock and the time difference of longitudinal wave and natural gamma value, the drillability of PDC bit, drillability, hardness, uniaxial compressive strength, abrasiveness and shear strength of the roller bit were measured in the laboratory. In order to establish the prediction model of drilling resistance parameters, we collected a certain number of core in the sub well section in Halahartang area, and conducted indoor test. The test results are shown in Table 4.

Table 4 core test results of Halahatang block

| Well | Depth | Drillability (cone bit) | Drillability (PDC) | Hardness compressive strength | Shear strength | Abrasiveness |
|------|-------|-------------------------|--------------------|-----------------------------|----------------|-------------|
| Ha1  | 4359  | 4.17                    | 3.39               | 436.38                      | 84.05          | 43.6        | 51.8        |
|      | 5291  | 6.58                    | 5.19               | 1581.26                     | 142.7          | 72.4        | 86.1        |
|      | 4803  | 4.82                    | 3.48               | 975.63                      | 105.6          | 58.4        | 78.1        |
|      | 5486  | 7.65                    | 6.1                | 1932.63                     | 193.95         | 86.5        | 92.67       |
|      | 5877  | 7.93                    | 6.85               | 2232.54                     | 221.2          | 101.4       | 101.7       |
|      | 6153  | 7.76                    | 6.47               | 2032.64                     | 208.3          | 98.3        | 97.47       |
| Ha5  | 3802  | 4.05                    | 3.14               | 368.62                      | 76.85          | 39.5        | 76.69       |
|      | 5891  | 7.84                    | 6.43               | 2135.2                      | 214.2          | 99.3        | 100.8       |
|      | 5960  | 7.15                    | 6.07               | 1771.14                     | 200.7          | 96.2        | 93.7        |
| Ha6  | 6305  | 7.62                    | 6.31               | 1912.6                      | 204.9          | 97.8        | 102.4       |
|      | 7043  | 6.38                    | 5.02               | 1463.6                      | 138.3          | 68.5        | 85.2        |

The relationships between PDC bit drillability level, cone bit drillability level, rock hardness, uniaxial compressive strength, formation abrasiveness, shear strength and P-wave time difference and natural gamma value of the above rock samples were plotted and analysed by scatter plot and correlation analysis. According to the correlation coefficient test table in modern statistical analysis method and application (sample number \( n = 11 \), significance level 5%, When the correlation coefficient \( r > 0.602 \) or the significance level is 1%, the correlation coefficient \( r > 0.734 \) can be regarded as linear correlation). The analysis shows that the above analysis parameters have significant linear relationship with P-wave time difference, but no obvious linear relationship with natural gamma value.
Taking the time difference of P-wave as the independent variable, taking PDC bit drillability level, cone bit drillability level, rock hardness, uniaxial compressive strength, formation abrasiveness and shear strength as the dependent variables, regression analysis was carried out according to linear function, power function, logarithmic function, exponential function model and polynomial model. According to the theory of one-way ANOVA in mathematical statistics, regression analysis was carried out with correlation coefficient R. The standard deviation S and the statistical test value F were used as the judgment criteria to analyse and verify the regression results, and finally the optimal fitting curve was selected. $(K = a^p \Delta T_{p2} + b^p \Delta T_p + c^p)$. a, b and c are correction coefficients, and different values should be selected according to the actual data in different areas. The relationship between drilling rock mechanics parameters and logging acoustic time difference is shown in Table 5.

| Parameter                      | Relationship                                      |
|--------------------------------|---------------------------------------------------|
| Drillability of cone bit PDC   | $K_{dpdc} = -0.0049\Delta T_{p2} + 0.6038\Delta T_p - 12.358$ |
| Drillability of cone bit       | $K_{dccone} = -0.0054\Delta T_{p2} + 0.6582\Delta T_p - 12.556$ |
| Hardness                       | $K_h = -2.4716\Delta T_{p2} + 301.77\Delta T_p - 7290.9$ |
| Compressive strength           | $K_c = -0.2128\Delta T_{p2} + 26.545\Delta T_p - 634.65$ |
| Abrasiveness                   | $\omega = -0.0382\Delta T_{p2} + 4.6288\Delta T_p - 45.988$ |
| Shear strength                 | $K_p = -0.0912\Delta T_{p2} + 11.34\Delta T_p - 261.05$ |

According to the above regression formula, the rock anti-drilling characteristic parameters of different well depths are calculated: PDC bit drillability grade value, cone bit drillability grade value, rock hardness, rock compressive strength and rock abrasiveness. Then, the least square fitting method is used to fit the curves of various anti-drilling characteristics, and the drawing function of MATLAB software is called to draw the profiles of anti-drilling characteristics of different formations, and the interface program between MATLAB and VB is used. The graph is sent back to the prediction software of formation anti-drilling characteristic parameters and displayed. The drillability profile of some wells in Halahatang block obtained by calculation, taking Ha 9 as example(Figure 5)

![Figure 5. Drillability Prediction results](image)

4. Field applications

The window prediction methods of safe mud density and formation drillability proposed in this paper are applied to 15 wells in Halahatang area. The average drilling cycle is 97.67 days (109.8 days before not applied), the average diameter expansion rate is reduced from 17% to 9.23%, and the drilling accidents are significantly reduced (Table 6). The research findings of this paper can guide the safe drilling operation in this area.

| Number | Well name | Drilling circle, days | Hole diameter enlargement rate,% |
|--------|-----------|-----------------------|----------------------------------|
|        |           |                       |                                  |

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|   |     |     |   |
|---|-----|-----|---|
| 1 | HH802 | 102 | 16.1 |
| 2 | HH803 | 98  | 8.5  |
| 3 | HH1202 | 97  | 9.5  |
| 4 | HH1204 | 113 | 6.2  |
| 5 | HH1002 | 90  | 11.0 |
| 6 | HH1005 | 89  | 18.1 |
| 7 | HH1601 | 104 | 12.4 |
| 8 | HH1602 | 104 | 5.5  |
| 9 | HH1604 | 92  | 6.4  |
|10| HH502 | 91  | 6.0  |
|11| HH503 | 100 | 11.9 |
|12| HH703 | 97  | 4.7  |
|13| HH912 | 101 | 8.6  |
|14| HH903 | 91  | 3.6  |
|15| HH9-2 | 96  | 10.0 |
|   | Average | 97.67 | 9.23 |

5. Conclusions

- The established safe mud density window can provide theoretical support for drilling fluid density design.
- The evaluation of formation drillability parameters based on P-wave time difference can provide basis for bit selection in Halahatang area.
- Three pressure prediction method and formation drillability prediction method have good field application effect (drilling cycle and diameter expansion rate are reduced by 12.4% and 45.7% respectively), which can effectively solve the problems of poor wellbore stability and low drilling speed in this area.

6. References

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