The method for prediction of formation pore pressure based on mechanical specific energy theory

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Abstract: With traditional prediction methods, the accuracy for prediction of formation pressure is low in formations with complex lithology, such as saline aquifers, fractured formations and carbonate rocks. Therefore, in Qinghai Oilfield, in order to ensure the drilling safety, studies have been conducted in order to find the method for predicting the pore pressure of E32 formation, in which the lithology is complex. Mechanical specific energy is the total energy required for breaking and removing rock per unit volume. With the increase of depth, the confining pressure of rock and vertical effective stress increase. Therefore, more energy is required to break and remove rock per unit volume. However, in abnormal high-pressure formation, pore fluid bears some overburden pressure, and the rock effective stress is reduced, leading to less requirement for mechanical specific energy. Therefore, it is feasible to evaluate the formation pressure qualitatively based on the mechanical specific energy theory. In this study, according to the actual drilling conditions, a model for prediction of formation pressure has been constructed and optimized on the basis of mechanical specific energy theory. With this model, the prediction accuracy on formation pressure has been improved obviously. This model has been used in prediction of formation pressure of the E32 formation in several wells in Qinghai Oilfield, which are carbonate rocks with fractures developed. The application results show that this formation pressure prediction model based on the mechanical specific energy works well in prediction of formation pore pressure, with an error less than 12%, which meets the engineering requirements. It provides a new method for predicting the pore pressure in complex lithologic formations such as carbonate rocks.

Key words: Formation pore pressure; mechanical specific energy; carbonate.

1. Introduction
Formation pressure refers to the pressure acting on the fluid within rock pores, also known as formation pore pressure. It is a very important formation parameter during drilling design, and can provide a great guidance for designing well profile, selecting appropriate drilling fluid and determining cement positions. A great deal of researches have been done on prediction of pore pressure [1-3] with many
prediction methods, such as equivalent depth method, Eaton method and effective stress method. However, all these methods have some limitations. First, most of the modelling methods are only applicable for mud shale formations. For complex formations such as carbonate rocks, the prediction accuracy is low; second, these methods can only be used for undercompacted formations. For complex high-pressure formations caused by multiple reasons, the prediction results are not reliable. Therefore, it is necessary to find a more scientific and effective pressure prediction method for oil and gas development in order to avoid drilling accidents.

In view of this, in this study, a new method for predicting formation pressure based on mechanical specific energy theory has been proposed. In the theory of mechanical specific energy, energy consumption is considered to solve the problems. This new method is applicable for complex formations such as carbonate rocks, as well as abnormal high-pressure formations with complex genesis. This method has been used for predicting the formation pressure of E32 Formation in several wells in Qinghai Oilfield, and good results have been obtained.

2. Theory of mechanical specific energy

2.1. Introduction

Mechanical specific energy is defined as the mechanical energy consumed to break rock per unit volume. It was proposed as a concept to describe bit performance, and provide a tool to evaluate drilling performance in real time. In China, few studies have been conducted on mechanical specific energy, and most of available studies are concentrated on bit selection, bit wear monitoring, drilling efficiency monitoring and evaluation while drilling, etc. [4-8]. The concept of mechanical specific energy was proposed by foreign scholar R. Teale. The mechanical specific energy is the work done by excavating unit volume of rock. The Teale formula is as follows [9]:

\[ MSE = \frac{WOB}{A_b} + 120\pi NT \frac{1}{A_b ROP} \]  

Where, \( MSE \) is the work needed to excavate the unit volume of rock, MPa; \( WOB \) is weight on bit, kN; \( A_b \) is drill bit area, mm\(^2\); \( N \) is rotary speed, r/min; \( T \) is the bit torque, kN\( \cdot \)m; \( ROP \) is the rate of penetration, m/h.

2.2. Optimization of model

Mechanical specific energy is defined as the mechanical energy consumed for crushing unit volume of rock. The mechanical specific energy model proposed by R. Teale is the most original one, but ignoring the hydraulic energy. During drilling strata with lower rock strength, the jet impact pressure can crush rock directly. Therefore, it is necessary to combine mechanical energy with hydraulic energy. That is to say, combine the bit torque (T) and weight on bit (W) with hydraulic energy effectively, so as to optimize the model according to actual drilling situations, and establish a new model of mechanical specific energy which is more compatible with a variety of bits.

2.2.1. Calculation of torque.

During rotation of the bit, torque is generated to rotate the bit. The torque will influence the bit efficiency. Torque is the product of force and arm of force. Xu Jiyin (1996)[10] proposed the calculation formula of torque according to former studies of predecessors:

\[ T = 6.07 \times 10^{-3} WD \]  

Where, \( T \) is the bit torque, kN \( \cdot \)m; \( W \) is the weight on bit, kN; \( D \) is the diameter of bit, mm.

2.2.2. Jet impact force.

Jet impact force refers to the resultant force of the jet flow in the bit nozzle acting on the bottom of well. Assuming that the mass of drilling fluid flowing through the bit nozzle is \( \Delta m \) within time \( \Delta t \), according to the momentum theorem, the formula is as follows:

\[ F_j \Delta t = \Delta m v_j \]
Then,

\[ F_j = \frac{\Delta m}{\Delta t} v_j = \rho_o Q \frac{Q}{A} = \frac{\rho Q^2}{A} \]  

(4)

This formula is deduced according to international standard units. Converted into units commonly used in oilfields, it is:

\[ F_j = \frac{\rho Q^2}{100 A_o} \]  

(5)

Where, \( F_j \) is jet impact force, kN; \( \rho \) is drilling fluid density, g/cm\(^3\); \( A_o \) is the cross-sectional area of nozzle outlet, cm\(^2\); \( Q \) is flow rate, L/s.

2.2.3. Calculation of bit pressure drop. Bit pressure drop refers to the pressure difference before and after the drilling fluid flowing through the nozzle of bit. The formula is as follows:

\[ \Delta P_b = \frac{0.05 \rho Q^2}{CA_o^2} \]  

(6)

Where, \( Q \) is the drilling fluid displacement, L/s; \( \Delta P_b \) is the bit pressure drop, MPa; \( \rho \) is the drilling fluid density, g/cm\(^3\); \( A_o \) is the total cross-sectional area of nozzle outlet, mm\(^2\).

2.2.4. Bit hydraulic horsepower. The bit hydraulic horsepower refers to the hydraulic horsepower given to the bit when drilling fluid flowing through the nozzle, that is, the hydraulic power consumed when drilling fluid flows through the bit. It can be expressed as follows:

\[ E_h = \Delta P_b Q \]  

(7)

Where, \( Q \) is the drilling fluid displacement, L/s; \( \Delta P_b \) is the bit pressure drop, MPa; \( E_h \) is the bit hydraulic horsepower, KW.

Generally, it is difficult to convert all the bit hydraulic horsepower into jet power to help rock breaking. The transfer efficiency or conversion efficiency of bit hydraulic horsepower depends on many factors, among of which, the ratio of nozzle flow rate to drilling fluid return rate is a main factor. \( Av \), the ratio of nozzle flow rate to drilling fluid return rate is expressed as:

\[ A_v = \frac{V_n}{V_f} = \frac{0.15 D^2}{n d_n^2} \]  

(8)

Where, \( A_v \) is the influence factor; \( V_n \) is the nozzle flow rate, m/s; \( V_f \) is the drilling fluid return rate, m/s; \( D \) is the diameter of bit, mm; \( n \) is the number of bit nozzles; \( d_n \) is the nozzle diameter, mm.

The transfer efficiency is:

\[ \eta = 1 - \left( A_v^p \right)^K \]  

(9)

Where, \( \eta \) is the transfer efficiency of hydraulic horsepower, dimensionless, between 0 and 1. Assuming \( K \) is 0.122 for calculation purposes.

2.2.5. Effective weight on bit. It is found that the impact force of the jet on the formation and the force on the bit are equal and opposite, and these forces conform to the Newton’s third law. As a result, the actual weight on bit applied to the formation must be different from ideal conditions, and will be reduced by the opposite force.
\[ W_{OB_e} = W_{OB} - \eta F_j \]  

(10)

Where, \( W_{OB_e} \) is the effective weight on bit, KN; \( W_{OB} \) is weight on bit, KN; \( \eta \) is the transfer efficiency of bit hydraulic horsepower, dimensionless.

2.2.6. Optimization of mechanical specific energy model. By combining the torque(T) and the weight on bit(W) with the bit hydraulic horsepower effectively, the transfer effect of bit hydraulic horsepower has been optimized in consideration of the actual drilling conditions, leading to a new mechanical specific energy formula, which is more consistent with the actual situations.

Based on the calculations above, the hydraulic mechanical specific energy (HMSE) can be defined as follows: the left-most part is the weight on bit energy, the middle part is the torque energy, and the right-most part is the hydraulic energy.

\[
\text{HMSE} = \frac{W_{OB_e} + 2.91N \times W_{OB_e}}{A_b \times \text{ROP}} + \frac{\eta \times \Delta p_b \times Q}{A_b \times \text{ROP}} 
\]

(11)

Where, \( \text{HMSE} \) is the hydraulic mechanical specific energy, MPa; \( W_{OB_e} \) is the effective weight on bit, KN; \( A_b \) is the bit area, mm\(^2\); \( N \) is the rotary speed, r/min; \( D \) is the bit diameter, mm; \( \text{ROP} \) is the rate of penetration, m/h; \( \Delta p_b \) is the bit pressure drop, MPa; \( Q \) is flow rate, L/s; \( \eta \) is transfer efficiency.

This hydraulic model has been improved and optimized on the basis of the original model. Considering the hydraulic energy, it is consistent with the actual drilling conditions. The hydraulic mechanical specific energy model solves the problem from the perspective of energy work, which is applicable for all types of drill bits, and can be used widely.

3. Prediction model of formation pressure based on mechanical specific energy

3.1. Influence of overbalanced drilling

During drilling, the bit will be influenced by many factors, and drilling fluid is one of the important factors. Overbalanced drilling is usually applied in drilling practice. After drilling into pressure transition zone, for the sake of safety, the density of drilling fluid will be increased usually. If the formation pressure is constant, the increased density of drilling fluid will increase the pressure, which will influence the normal change of mechanical specific energy, resulting in lower ROP and higher mechanical specific energy. In order to eliminate the influence of drilling fluid density, the mechanical specific energy formula was corrected as follows:

\[ \text{HMSE}_{F} = F \times \text{HMSE} \]

(12)

\( F \) is the overbalance correction factor, which can be calculated via the following formula:

\[ F = 1 + \frac{1 - \sqrt{1 + n^2 \Delta p^2}}{n \Delta p} \]

(13)

Where, \( \Delta p \) is the pressure difference between the hydrostatic pressure of the drilling fluid and the formation pore pressure. It can be calculated via the following formula:

\[ \Delta p = \left( \rho_m - \rho_n \right) \frac{h}{10 \text{bar}} \]

(14)

Where, \( \rho_m \) is the actual drilling fluid density, g/cm\(^3\); \( \rho_n \) is the equivalent drilling fluid density under normal formation pressure, g/cm\(^3\); \( h \) is the well depth, m; \( \Delta p \) is the pressure difference, bar (10\(^5\)Pa).

\( n \) is a function of the time required to compensate for the pressure difference between the hydrostatic pressure of the drilling fluid and the formation pore pressure, which mainly depends on the lithology and porosity of the formation itself. The formula for \( n \) is as follows:
\[ n = \frac{3.25}{640 \sqrt{H M S E}} \]  

(15)

As can be seen from the formula above, when the drilling fluid density is equal to the equivalent density under normal formation pressure, \( \Delta p \) is equal to zero. When \( \Delta p \) approaches to 0, \( F \) approaches to 1, then \( HMSE_r = F \times HMSE = HMSE \).

3.2. Normal trend line of mechanical specific energy

Mechanical specific energy is the total energy required to break and remove rock per unit volume. With the increase of depth, the confining pressure and vertical effective stress of the rock increase, and more total energy is required to destroy and remove the rock per unit volume. Under normal formation conditions, the plotted HMSEF-depth curve is a straight line with a certain slope after eliminating the effect of overbalance. This line is the ideal normal trend line to build HMSEF. Regression method is usually used to build the normal trend line, and its regression equation is as follows:

\[ HMSE_r = a \frac{h}{1000} + b \]  

(16)

Where, \( HMSE_r \) is the mechanical specific energy of the normal trend line, MPa; \( h \) is the vertical depth, m; \( a \) is the slope of normal trend line; \( b \) is the intercept of normal trend line.

3.3. Evaluation of formation pressure based on mechanical specific energy

In normal formations, HMSEF increases with the increase of buried depth. However, in abnormal high-pressure formations, the effective stress of rock decreases, and the bottom hole pressure difference changes, HMSEF deviates from the normal trend line. When HMSEF curve deviates from the normal trend line to the left, indicating less energy consumption by the formation and high-pressure formation exists. On the contrary, when HMSEF curve deviates from the normal trend line to the right, indicating more energy consumption by the formation and cap rock maybe exist.

The equivalent density under formation pressure is usually converted by comparing the measured values with the normal trend line values, and the relationship between these parameters can be expressed as:

\[ \Delta p = 2 \left( 1 - \frac{HMSE_r}{HMSE} \right) \left( 1 - \left( 1 - \frac{HMSE_r}{HMSE} \right)^2 \right) \frac{1}{n} \]  

(17)

The calculated \( \Delta p \) can reflect the actual conditions in the well, and it can be used to calculate the equivalent drilling fluid density under real formation pressure:

\[ \rho_p = \rho_m - \frac{10 \Delta p}{h} \]  

(18)

Where, \( \rho_p \) is the equivalent drilling fluid density under formation pressure, g/cm\(^3\); \( \rho_m \) is real drilling fluid density, g/cm\(^3\); \( \Delta p \) is the pressure difference, bar(10\(^5\)Pa); \( h \) is the well depth, m.

Mechanical specific energy method is used to judge whether the formation has high pressure by doing work on the unit volume of rock. It is not limited to the undercompacted high-pressure formations. Actually, it is applicable to a wide range of formations, such as shale and carbonate rocks. Due to the simple and clear calculations with less parameters required, it is a good method for predicting formation pressure.
3.4. Algorithmic steps for calculating formation pore pressure with mechanical specific energy method

(1) Logging data at depth intervals recorded by comprehensive logging instruments or drilling parameter loggers, including depth (m), weight on bit (kN), rotary speed (r/min), rate of penetration (m/h), and drilling fluid density (g/cm³), drilling fluid flow rate (L/s),

(2) Bit use data: bit RIH and POOH depth (m), bit diameter (mm), bit model, number of bit nozzles (mm), nozzle diameter (mm).

(3) Geological stratification data: bottom boundary depth (m), formation code or name.

![Algorithm Flow](image)

4. Case study in Qinghai Oilfield

Firstly, Well Shi 41-4 in the middle of Yingxi region was taken as the typical well for model verification. In Well Shi 41-4, some formations are carbonate rocks, with complex geological conditions. In addition, due to the combination of undercompaction and structural compression, abnormal high pressure exists in these formations. When drilling to depth of 4593.43m, drilling fluid started to overflow, with a total of 8.0m³ drilling fluid flowing out, and the density of drilling fluid was 1.8g/cm³. The overflow interval is at depth of 4593.00-4593.96m in E32 formation, which is mainly gray argillaceous carbonate rocks.

4.1. Plot mechanical specific energy HMSE--well depth curve and normal trend line

According to the formulas mentioned above, the drilling and logging parameters of Well Shi41-4 were calculated to obtain the initial mechanical specific energy data, which had to be filtered to remove the data with large errors and the isolated points not consistent with the actual working conditions.
As shown in Fig. 2, at depth of 4500-4700m, the mechanical specific energy curve deviates to the left, which indicates the existence of abnormal high pressure, with the maximum deviation at depth of 4600m.

4.2. Calculation of pore pressure
The pore pressure has been obtained, which is shown as follows:

As shown in Fig. 3, high pressure appears at depth of 4400-4700m, with maximum of 1.88g/cm$^3$ approximately. The well history shows that when drilling to the depth of 4593.43m, drilling fluid started to overflow, and the equivalent density under formation pressure was about 2.02 g/cm$^3$. The error between the calculation result and actual value is 10%. The calculation results are consistent with the actual drilling conditions. In addition, the abnormal high-pressure has been predicted. Therefore, it is proved that this method is suitable for carbonate rocks in Yingxi region, and the calculation process is simple and practical.

4.3. Case studies and comparison results
Excellent prediction results have been obtained from case study in Well Shi 41-4 as described in the section above. In this section, some typical wells in carbonate rocks were picked out in Yingxi region and Yingzhong region for comparison and analysis. Similarly, in these typical wells, complex lithology and abnormal high-pressure formations with fractures were encountered.
### Table 1. Comparison between the predicted pressure and measured pressure

| Well name          | Well depth/m | Measured pressure coefficient | Predicted pressure coefficient | Relative error/% |
|--------------------|--------------|-------------------------------|--------------------------------|-----------------|
| Shi 41-3           | 2997         | 1.011                         | 0.951                          | 6.3             |
|                    | 3049         | 1.031                         | 0.961                          | 7.3             |
|                    | 2370         | 1.176                         | 1.055                          | 11.5            |
| Shi 49-1           | 3235         | 1.65                          | 1.5                             | 10              |
|                    | 3780         | 2.02                          | 1.843                          | 9               |
| Shi 47 side well   | 3505         | 1.342                         | 1.237                          | 8.5             |
|                    | 3700         | 1.453                         | 1.348                          | 7.8             |
|                    | 4400         | 1.923                         | 1.74                           | 10.5            |
|                    | 2280         | 1.04                          | 0.949                          | 9.6             |
| Shi 52-1           | 3110         | 1.166                         | 1.105                          | 5.5             |
|                    | 3400         | 1.221                         | 1.11                           | 10              |
|                    | 4713         | 2                             | 1.8                            | 10              |
| Shi 65             | 4889         | 2.415                         | 2.15                           | 11              |
|                    | 5321         | 2.556                         | 2.25                           | 12              |
|                    | 4944         | 2.24                          | 2.05                           | 8.5             |
| Shi 58-1           | 5146         | 2.223                         | 2.05                           | 7.8             |
|                    | 5770         | 2.402                         | 2.15                           | 10.5            |

With this prediction model, quantitative analysis has been conducted on the formation pressure in some wells in carbonate rocks in Yingxi and Yingzhong regions. Comparing with the drilling history, it is found that the predicted pressures are basically consistent with the actual values. The prediction error is under 12%, which further proves the wide applicability and accuracy of this model for prediction of formation pressure even in complex lithological formations.

### 5. Conclusions

Mechanical specific energy is defined as the mechanical energy consumed to break rock per unit volume. In this study, the original mechanical specific energy formula has been optimized according to actual drilling conditions, and a new hydraulic mechanical specific energy formula has been established, which can reflect the actual drilling conditions. This hydraulic mechanical specific energy model can solve the problem from the perspective of energy consumption, and is suitable for complex lithology such as carbonate rocks.

Overbalanced drilling is usually conducted in the drilling practice, which often affects the normal change of mechanical specific energy. Therefore, the mechanical specific energy should be corrected to obtain the real mechanical specific energy. In normal formations, the mechanical specific energy increases gradually with the increase of buried depth. However, in abnormal high-pressure formations, the effective rock stress decreases, and the bottom hole pressure difference changes, leading to less energy consumption. Therefore, the curve of mechanical specific energy will deviate from the normal trend line. By plotting the mechanical specific energy - well depth curve, filtering and eliminating the error points by algorithms, the normal trend line of mechanical specific energy has been established, and then the formation pressure has been calculated.

With this model, analysis has been conducted on the formation pressure of carbonate rocks in Wells Shi 41-3, Shi 41-4, Shi 49-1, Shi 47 side well, Shi 52-1, Shi 58-1 and Shi 65 in Yingxi and Yingzhong regions of Qinghai Oilfield, and the formation pressure distribution has been obtained, with an error within 12%. This has proved that this method is simple and applicable for prediction the formation pressure of carbonate rocks.
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