Stress distribution model of hard and brittle mud shale based on hydration damage

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Abstract. Hard and brittle shale developed in the middle and deep layers of the Bohai Sea cause severe challenges in drilling. During the drilling process, drilling fluid easily penetrates the rock along the microcracks, which leads to the deterioration of the mechanics and strength parameters of the rock. This consequently changes the stress distribution in the borehole wall. In addition, the fluid seepage hydrates the rock, which affects the relationship between the change in water content at any position and at any time in the rock mass is solved. The hydration equivalent of the elastic modulus is regarded as damage evolution, and a damage tensor considering hydration is introduced. A constitutive relationship of hard and brittle mud shale considering the effect of hydration damage is established, and the stress distribution around the well of the hard and brittle mudstone under non-uniform stress is solved by a semi-numerical and semi-analytical method. In addition, the influence law of hydration damage on the stress distribution around the well is analyzed. Taking an 8-1/2-inch section of an exploratory well in the Bozhong 19-6 gas field as an example, the stress distribution and collapse pressure analysis of the well bore revealed that after the section of the well was drilled for 100 h, the formation stiffness caused by hydration damage significantly decreased and borehole instability occurred inside the borehole wall. The risk of collapse was greater in the direction of the smallest in situ stress. The effect of hydration expansion on the stress distribution was limited, showing only a slight effect on the tangential stress near the well wall. The collapse of hard and brittle mud shale is mainly related to deterioration of the rock stiffness performance and strength parameters caused by hydration damage. The section incurred a short period of collapse, in which the maximum diameter expansion rate was equivalent to 5.9%, and the density of drilling fluid used on site was relatively low. Therefore, the density of the drilling fluid should be appropriately increased to enhance its sealing properties. The model reveals the hydration collapse mechanism of hard and brittle shale to a certain extent, which provides a theoretical basis for the safe and efficient drilling in similar formations.

Keywords. hard and brittle mud shale; hydration damage; elastic modulus; constitutive relationship; stress distribution

1. Introduction

Hard and brittle mud shale developed in the Dongying and Shahejie formations of the Bohai Sea have an adverse effect on the safe and efficient drilling of the medium and deep layers of these foundations. Initial microcracks in this shale enable drilling fluid to easily enter the rock, which causes hydration and weakens the mechanical and strength parameters of the rock. This consequently leads to changes in the stress distribution in the borehole wall.

In early research of mud shale hydration abroad, some studies [1-6] used a mechanical and chemical coupled calculation model combined with experimental analysis to consider the influence of confining pressure and mud intrusion on the strength of mud shale. Others studies [7-11] considered the physical and chemical effects of drilling fluids and mudstones and their coupled thermal factors to develop analytical or numerical methods for analyzing the instability of the borehole wall. Domestic scholars have also conducted abundant research on shale hydration in wells based on mechanical and chemical coupled models. In theoretical analysis, Huang, Deng, Meng, and others [12-19] established a shale stress–strain constitutive equation under uniform in situ stress based on the characteristics of mud shale hydration and used analytical and numerical methods to
investigate the hydration stress occurring around the well. In addition, they considered the effect of water content on the strength and mechanical parameters of the rock to analyze the laws related to the collapse cycle of the shaft wall. In terms of experiments, Deng [13] and Xu [20] measured parameters such as the water absorption diffusion coefficient, permeability, and membrane efficiency of mud shale. Sheng and Zhang [21,22] used the finite element platform to analyze the permeability characteristics of rock fractures. Huang [23] studied the effect of drilling fluid on the strength of mud shale. However, in-depth research is still lacking on the stress distribution of mudstone around wells considering hydration damage under the non-uniform in situ stress condition.

This study analyzes the diffusion law of shale water absorption with time and distance from the well center. Then, the change rule of mechanical performance parameters with hydration is determined. A damage evolution model established on the basis of the damage theory is used to reveal the damage evolution law of the combined action of stratum after water absorption and the complex underground environment. In addition, the period of damage and instability of the surrounding mudstone rock was determined. Finally, the corresponding engineering countermeasures for mid-deep hard and brittle mudstone drilling are proposed to provide a technical basis and theoretical guidance for the safe drilling of such wells. The novelty and creativity of this study is that a semi-numerical and semi-analytical method is used to calculate the stress distribution around the borehole considering hydration damage under the non-uniform in situ stress condition.

2. Hydration action

2.1. Calculation of water content

For the hydration action of rocks, according to the conservation of fluid quality, the water absorption and diffusion equation of the rock surrounding the shaft wall can be established. By solving the definite solution problem based on the water content boundary conditions, the water content at any position and any time of the rock body and the change relationship of the rock elastic modulus with the water content can be obtained. The water content and elastic modulus [13] are calculated as

\[ w(r,t) = w_0 + (w_s - w_0) \text{erfc}(\frac{r}{2\sqrt{c_f}t}) \]  

\[ E(r,t) = E_o e^{-C_e(w-w_0)0.5} \]  

In Eq. (1), \( \text{erfc}() \) is the error compensation function, \( w \) is the water content of the mudstone, \( r \) is the distance from the center of the wellbore, \( t \) is time, \( w_s \) is the saturated water content, \( w_0 \) is the original water content, and \( c_f \) is the diffusion coefficient of the mudstone. In Eq. (2), \( E_o \) is the initial value of the elastic modulus and \( C_e \) is the hydration coefficient of the elastic modulus, which can be determined according to experiments for different rocks [13]. The specific experimental process is described in detail in literature [13] and is not repeated here.

To investigate the relationship between the water content \( w(r,t) \) and elastic modulus \( E(r,t) \) with time \( t \), the following values were determined to obtain the curve shown in Fig. 2: \( w_s = 12\% \), \( w_0 = 5\% \), \( E_o = 20 \) GPa, \( C_e = 11 \), and \( c_f = 0.0092 \) cm²/h. As shown by curve 1(a) in the figure, at a certain time, the water absorption of mudstone decreases as the distance from the wellbore increases, and a hydration zone is formed in the mudstone formation around the wellbore. After a certain distance, the water content is close to the original water content. In the hydration zone, when the distance is fixed, the mudstone’s water absorption increases with time and eventually becomes saturated and tends to stabilize. Curve 1(b) shows that the borehole is affected by drilling fluid intrusion such that the water cut is saturated and the formation elastic modulus significantly decreases. As the distance from the borehole wall increases, the elastic modulus tends to the return to the original value and increases with time. The elastic modulus then decreases, and the leading edge tends to be deep in the formation. The deterioration of the elastic modulus will inevitably affect the stress distribution around the well, which consequently will cause the rock collapse pressure to change.
2.2. Continuous hydration damage analysis

Combining the definition of elastic modulus hydration and damage modulus elastic modulus reduction shown in Eq. (2) [24], the hydration of elastic modulus can be equivalently regarded as damage evolution. Then, the following hydration damage tensor of hard and brittle mud is obtained as

\[
D = \begin{bmatrix} h(w) & h(w) & h(w) \\ h(w) & h(w) & h(w) \\ h(w) & h(w) & h(w) \end{bmatrix}
\]

(3)

where \( D \) is the damage variable and \( h(w) \) is the hydration damage function.

The meso-damage evolution of the rock under loading will cause obvious stiffness attenuation at the damage location. In this study, the damage tensor is used to analyze the elastic parameters at each time step [25]:

\[
E = E_0 \times (1 - D)
\]

(5)

where \( E \) is elastic modulus matrix for damage. Using Eq. (5) for damage analysis, the continuous damage evolution behavior of a rock under hydration can be obtained.

3. Solution of stress distribution considering hydration

The stress analysis of hard and brittle mudstone under non-uniform stress can be characterized by Fig. 1.
Fig. 2a can be decomposed into superpositions of a uniform boundary and a non-uniform boundary, as shown in Figs. 2a and 2b, respectively. The blue area in the figure is the hydration zone. In the analysis, the weakening of mechanical parameters caused by hydration damage should be considered.

For the uniform boundary problem, the stress at the infinity of the formation can be regarded as equal (Fig. 2a). In this case, the stress–strain relationship around the borehole under the plane strain state, that is, the constitutive equation, can be expressed as

\[
\varepsilon_r = \frac{1}{E} \left[ \sigma_r - \mu (\sigma_\theta + \sigma_z) \right] + \varepsilon_h
\]

\[
\varepsilon_\theta = \frac{1}{E} \left[ \sigma_\theta - \mu (\sigma_r + \sigma_z) \right] + \varepsilon_h
\]

\[
\varepsilon_z = \frac{1}{E} \left[ \sigma_z - \mu (\sigma_r + \sigma_\theta) \right] + \varepsilon_h
\]

where \( E \) and \( \mu \) are the elastic modulus and Poisson's ratio of the shale, which are no longer constant and change owing to the influence of hydration damage in the formation.

During the drilling process, the hard and brittle mudstone is in contact with the drilling fluid, and the water in the drilling fluid penetrates the formation. During the process of the mudstone water absorption, expansion strain will occur, which can be expressed as

\[
\varepsilon_v = K_1 (w-w_o) + K_2 (w-w_o)^2
\]

The expansion strain perpendicular to the bedding direction is higher than that parallel to the bedding direction, \( \varepsilon_h = m \varepsilon_v \) \((0 < m \leq 1)\). In general, for medium and deep layers of hard and brittle mud shale, the small amount of expandable clay minerals is compensated by two expansion empirical coefficients: \( K_1 = 0.0112 \) and \( K_2 = 0.00201 \).

Combining the equilibrium state and geometric equations of the medium around the wellbore, Eq. (7) can be obtained through a series of derivations:

\[
r \frac{d^2 \sigma_r}{dr^2} + \left( 3 - \frac{r \frac{dE}{dr} + 2v \frac{dv}{dr}}{v^2 - 1 \frac{dv}{dr}} \right) \frac{d\sigma_r}{dr} + \left( \frac{4v + 1}{v^2 - 1} \frac{dv}{dr} - \frac{1}{v - 1} \frac{dE}{dr} \right) \sigma_r = \frac{E (m + v) \frac{dv}{dr}}{v^2 - 1} + \frac{E \varepsilon_v \frac{dv}{dr}}{v^2 - 1}
\]

The components of Eq. (7) are defined as

\[
\begin{align*}
    f_1 &= r \\
    f_2 &= 3 - \frac{r \frac{dE}{dr} + 2v \frac{dv}{dr}}{v^2 - 1 \frac{dv}{dr}} \\
    f_3 &= \frac{4v + 1}{v^2 - 1} \frac{dv}{dr} - \frac{1}{v - 1} \frac{dE}{dr} \\
    f_4 &= \frac{E (m + v) \frac{dv}{dr}}{v^2 - 1} + \frac{E \varepsilon_v \frac{dv}{dr}}{v^2 - 1}
\end{align*}
\]

Then, Eq. (8) can be converted to

\[
f_1 \sigma_r + f_2 \sigma_\theta + f_3 \sigma_z = f_4
\]

Deng [16] solved Eq. (9) using the finite difference method in which the hydration stress distribution around the well was obtained under the condition of uniform in situ stress. The specific solution method is not repeated here.

In the case of non-uniform boundaries, the hydration stress distribution of the rock surrounding the shaft wall no longer satisfies the axisymmetric conditions. However, the changes in mechanical and strength parameters with hydration damage still need to be considered in the solution process. The stress distribution under the non-uniform boundary conditions is
After solving Eq. (10), the formula can be superimposed with the stress distribution in the uniform boundary case, and the coupling stress distribution considering hydration damage under non-uniform stress conditions can be obtained.

4. Case analysis

In the Bozhong 19-6 structure located in the southwestern part of the Bozhong Depression, more than 10 exploratory wells have been drilled thus far. The above model was used to calculate and analyze the stress distribution and collapse pressure of an 8-1/2-inch section of the X well in the BZ19-6 gas field based on hydration stress damage. Abundant hard and brittle mud shale was encountered when drilling in this section, which began in the No. 2 east formation and ended at the top of the buried hill formation. To penetrate the mud shale, the section was drilled using a polycrystalline diamond compact (PDC) bit. Since abnormally high pressure was developed, the polymer electrolyte membrane (PEM) drilling fluid system was employed; the mud density used was 1.4 g/cm³. The depth of 4070 m, which is the point at which the well diameter expansion occurred, was taken as an example for calculation analysis. Table 1 shows the relevant calculation parameters of the well at this depth.

| Parameter                          | Value         |
|-----------------------------------|---------------|
| TVD                               | 4070 m        |
| Equivalent density of overburden  | 2.30 g/cm³    |
| Horizontal maximum stress equivalent density | 1.98 g/cm³    |
| Horizontal minimum stress equivalent density | 1.80 g/cm³    |
| Pore pressure equivalent density  | 1.39 g/cm³    |
| Drilling fluid density            | 1.40 g/cm³    |
First, the hydration damage of the well section was analyzed after using the PEM system for 100 h. As shown in the calculation results in Fig. 4, after using the drilling fluid for a long time, the drilling fluid was inevitably filtered into the formation, resulting in damage to the formation and a decrease in rock rigidity. The damage factor was greater than 0.9 at the borehole wall and up to 0.27 at the borehole radius of 2 times; deeper boreholes were less affected by the damage.

![Figure 4](image)

Figure 4 Change in damage variable $D$ with normalized radius

The curve of radial stress and tangential stress at the depth of the well wall under conditions of 50 h and 100 h of hydration as well as no hydration is shown in Fig. 5. The hydration had little effect on the radial stress, whereas the tangential stress near the wellbore sharply decreased. This might be attributed to the rock’s weakened resistance to deformation owing to hydration, although the water absorption expansion caused the wellbore expansion stress to increase. However, the reduction of rock deformation stiffness had a greater impact on the stress. With the increase in hydration time, hydration damage developed deep inside the well wall. The tangential stress increased at depths of 3–6 cm inside the well wall, where the maximum value of the peak hydration stress occurred. This indicates that the wellbore instability first occurred at a certain depth inside the wellbore wall rather than at the shaft wall. In addition, when considering the non-uniformity of in situ stress, the difference between the tangential and radial stress at the minimum in situ stress was greater, and the risk of mudstone collapse increased, which is consistent with the collapse orientation without considering hydration. However, hydration caused the collapse to occur first inside the well wall, which exacerbated the risk of jamming.

![Figure 5](image)

Figure 5 Distribution of hydration stress around well BZ19-6-X at minimum and maximum horizontal stresses
Fig. 6 shows the calculation results of the effect of hydration expansion on stress distribution in Well BZ19-6-X. The hydration expansion property had a limited effect on the stress distribution, showing a weak effect on the tangential stress near the well wall, because the hard and brittle mud shale contains less expansive clay minerals. In addition, the hydration expansion coefficients $K_1$ and $K_2$ were very small, resulting in little influence on the stress distribution. Therefore, the collapse of hard and brittle mud shale was mainly related to the reduction of rock stiffness performance caused by hydration damage and deterioration of the strength parameters of the matrix and bedding structure plane, which is quite different from the collapse mechanism of shallow expansive soft mudstone.

![Figure 6](image_url)  
**Figure 6** Effect of hydration expansion on stress distribution in the BZ19-6-X well

The hydration collapse pressure first decreased and then increased with time, as shown in Fig. 7. However, the collapse pressure can reach the initial collapse pressure value after about 20 h owing to the strong hydration, and then, the rising trend of collapse pressure gradually slowed down. The initial collapse pressure was 1.32 g/cm$^3$, which was reached about 100 h after uncovering the 4070 m formation. After 100 h, the collapse pressure increased to 1.42 g/cm$^3$ owing to drilling fluid hydration. The mud density used in this well is 1.40 g/cm$^3$, which is lower than the collapse pressure value after 100 h of hydration. Subsequent on-site borehole diameter logging data shows that after the 8-1/2-inch borehole was drilled, the borehole diameter slightly expanded at a rate equivalent to about 5.9%. In general, mudstone hydration results in a short period of formation collapse. Therefore, to avoid large-scale collapse caused by the loss of drilling fluid along the rock layer, the drilling fluid density should be appropriately increased to enhance its sealing properties. Moreover, the section should be drilled as quickly as possible and the casing should support the rock mass to prevent hydration by the drilling fluid.

![Figure 7](image_url)  
**Figure 7** Time-varying law of collapse pressure in mudstone formation
5. Conclusions and suggestions
(1) The change in water content at any position of the rock mass at any time as well as the change relationship of the rock’s elastic modulus with the water content are obtained in rock hydrated by drilling fluid. The water content tends to be saturated near the well wall, and the elastic modulus of the rock significantly decreases. The hydration equivalent of elastic modulus is regarded as damage evolution, and a damage tensor considering hydration is introduced.

(2) The stress of mudstone under non-uniform conditions is decomposed into the superposition of uniform and non-uniform stress conditions. The stress distribution around the mudstone well considering hydration damage is solved by applying a combined semi-numerical and semi-analytical method.

(3) The stress distribution of the 8-½-inch borehole in an exploratory well X in BZ19-6 gas field is analyzed considering hydration damage. In this case, the instability of the wellbore first occurs inside the wellbore wall rather than in the shaft wall. When considering the non-uniformity of in situ stress, the risk of collapse at the minimum in situ stress orientation is greater, which is consistent with the collapse orientation without considering hydration. The effect of hydration expansion on the stress distribution is limited, showing only a slight effect on the tangential stress near the well wall. Therefore, the collapse of hard and brittle mud shale is mainly related to the decrease in rock stiffness performance caused by hydration damage and the deterioration of the strength parameters of the matrix and bedding structure planes.

(4) The calculated collapse pressure significantly increases. In addition, the on-site expansion rate of the borehole diameter after drilling for a long period is shown to be equivalent to 5.9%, indicating low density in the drilling fluid.

Hydration damage is reduced by improving the plugging properties of drilling fluids and reducing their filtration loss to the rock formation, which resolves the site collapse of hard and brittle mudstone formations. Moreover, in formations containing microfractures, further mechanical collapse of the borehole wall is avoided by properly increasing the drilling fluid density, which strengthens the plugging effect.

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