Research on borehole stability of shale based on seepage-stress-damage coupling model

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ABSTRACT. In oil drilling, one of the most complicated problems is borehole stability of shale. Based on the theory of continuum damage mechanics, a modified Mohr-Coulomb failure criterion according to plastic damage evolution and the seepage-stress coupling is established. Meanwhile, the damage evolution equation which is based on equivalent plastic strain and the permeability evolution equation of shale are proposed in this paper. The physical model of borehole rock for a well in China western oilfield is set up to analyze the distribution of damage, permeability, stress, plastic strain and displacement. In the calculation process, the influence of rock damage to elastic modulus, cohesion and permeability is involved by writing a subroutine for ABAQUS. The results show that the rock damage evolution has a significant effect to the plastic strain and stress in plastic zone. Different drilling fluid density will produce different damage in its value, range and type. This study improves the theory of mechanical mechanism of borehole collapse and fracture, and provides a reference for the further research of seepage-stress-chemical-damage coupling of wall rock.

KEYWORDS. Shale; Seepage-stress coupling; damage; Permeability; Finite element method; Borehole stability.

INTRODUCTION

In oil drilling, the study of borehole stability is a complicated task which involved with many factors. Different researchers studied in different aspects [1] includes non-uniform ground stress, drilling fluid [2], bottom hole temperature [3] and fluid-structure coupling [4], etc. However, most researchers consider that mechanics is the primary cause of borehole instability. Other factors can change the rock mechanics properties or stress state in different degrees. At present, there are several models applied to analyze borehole stabilization, such as liner elastic model, elastic-plastic model [5] and fluid-solid coupling model of porous media [4]. However, most of studies pay little attention to rock damage. Practically,the stress redistribution after excavation will cause the produce of damage (Fig.1). In the process of rock damage, permeability will change greatly with the fracture producing, extending and connecting [6]. Meanwhile, rock strength and elastic modulus will decrease obviously. All of this can effects the result of force analysis, so it is necessary to involve the damage in seepage-stress coupling calculation of wall rock.

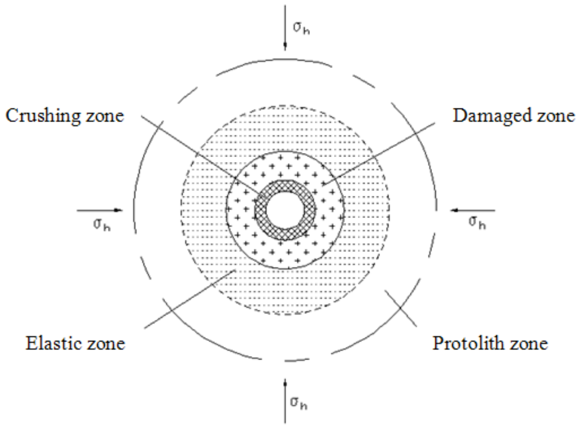

Figure 1: Damage zone of wall rock in the uniform ground stress.

Under the change of external load or environment, the macro-mechanical properties deterioration of materials or structure caused by the initiation and propagation of microstructure defects (such as micro-cracks, micro-porosity, etc.) or other irreversible changes is called damage. In the study of seepage in fractured rock mass of damage mechanics, Yi [7] established a seepage-damage coupling model, and a damage evolution equation in the compression shear or tensile shear state. Zheng [8] proposed a seepage-damage coupling theory and a permeability tensor expression which considered the effect of damage of fractured rock. Jiang Tao [9] deduced a damage constitutive model and a seepage-damage constitutive model of brittle rock based on mesomechanics. Yang [10] and Zhao [11] studied the seepage-damage-fracture coupling theory and its application. Based on poroelastic theory, Selvadurai [12] studied the damage and permeability variation of geological materials which relate to stress. For the rock, the meaning of plasticity mainly refers to the sliding between inner fissuring. But the damage refers to the producing and extending of inner fissuring. The damage means a decrease of net loaded area in geometry. Using the plastic-damage coupling constitutive model, the mechanical behaviour could be represented exactly.

Based on the theory of continuum damage mechanics, the damage evolution model according to equivalent plastic strain is established in this paper. Additionally, the permeability evolution equation is established in relation to the evolution of plastic damage. Aiming at a practical drilling process in an oilfield in western China, the physical model of borehole rock is built. Using this model to simulate the disturbance damage and the permeability evolution in drilling, the distribution of stress of wall rock and the relationship between borehole instability and drilling fluid density is obtained. This study will improve the theory of mechanical mechanism of borehole collapse and fracture.

SEEPAGE-STRESS-DAMAGE COUPLING MODEL

Nonlinear behaviour of rock caused mainly by micro cracks. If the micro cracks become a macro-fracture by accumulating, extending and connecting, then the degradation of material property which includes the strength, rigidity and ductility will arise. For describing it, the damage variable is needed according to irreversible thermodynamics. The damage variable can be chosen from the characteristics of micro-structure (the quantity, length, area and volume of micro cracks) or the experiment date (the elastic modulus, strain, yield stress, density and wave velocity). To apply the model in practical engineering, the damage variable and its evolution law is need to define. In this paper, the damage variable is supposed as follows:

1) Rock damage occurs and increases with plastic deformation simultaneously.

2) The rate of damage rise is gradually diminishing with the development of plastic deformation.

ELASTIC-PLASTIC DAMAGE MODEL

The effective shear strength parameters c^* and ϕ^* is influenced by rock damage [13]. So the c^* and ϕ^* is a function of damage state. When the effect of damage and pore pressure is involved, the Mohr-Coulomb failure criterion can be indicated as Eq. (1).

$$\frac{\tau_n}{1-\Omega} = c^* + \frac{\sigma_n + \Omega p_w}{1-\Omega}\tan\phi^* \tag{1}$$

where:
- Ω is damage variable;
- σ_n and τ_n are stresses on the failure surface;
- p_w is the pore pressure.

In this paper, the internal frictional angle is deemed to be changeless. But the cohesion will decrease gradually with the accumulation of damage. Their relationship can be represented by a power-law function:

$$\bar{c} = c_m - \left(c_m - c_r\right)\Omega_p^{\eta} \tag{2}$$

where:
- c_m is the cohesion of shale with no damage;
- c_r is the cohesion of shale with complete damage;
- η is the material parameter, $0 \le \eta \le 1$.

The elastic modulus of the damaged shale is:

$$\overline{E} = \left(1-\Omega\right)E_0 \tag{3}$$

where E_0 is elastic modulus of shale with no damage.

According to (3), $\overline{E} = 0$ when $\Omega = 1$. This does not match the actual reality. In fact, the rock also has a certain elastic modulus after damage. So, Eq. (3) needs to modify as:

$$\overline{E} = E_0 - \left(E_0 - E_r\right)\Omega \tag{4}$$

where E_r is elastic modulus of shale with complete damage.

DAMAGE EVOLUTION EQUATION

If the stress exceeded rock strength at the condition of fluid-solid coupling, plastic deformation will be produced in wall rock. The equivalent plastic strain is:

$$\bar{\varepsilon}_p = \frac{\sqrt{2}}{3}\sqrt{\left(\varepsilon_{p1}-\varepsilon_{p2}\right)^2 + \left(\varepsilon_{p2}-\varepsilon_{p3}\right)^2 + \left(\varepsilon_{p3}-\varepsilon_{p1}\right)^2} \tag{5}$$

where ε_{p1}, ε_{p2} and ε_{p3} are the three principal plastic strains.

In this paper, the damage variable is the first order index decay function of equivalent plastic strain which is as follows [14]:

$$\Omega = A_0 e^{-\bar{\varepsilon}_{pn}/a} + B_0 \tag{6}$$

$$A_0 = \frac{1}{e^{-1/a} - 1};\; B_0 = -\frac{1}{e^{-1/a} - 1}$$

where $\bar{\varepsilon}_{pn}$ is normalized equivalent plastic strain; a is material parameter which can be measured by experiments.

PERMEABILITY EVOLUTION EQUATION

In the stage of elastic deformation, rock permeability is decreasing when the compression stress increases. When plastic deformation takes place, rock permeability will increase slowly first and then sharply with the new crack extending and connecting. The permeability evolution equation of shale under different stress states can be indicated as follows [15]:

$$k_d = \begin{cases} k_0\left[\left(\dfrac{1}{n_0}\right)(1+\varepsilon_v)^3 - \left(\dfrac{1-n_0}{n_0}\right)(1+\varepsilon_v)^{-1/3}\right]^3, \Omega = 0 \\ k_0 \cdot 10^{m\left(Ae^{-\Omega/\alpha}+B\right)}, \Omega > 0 \end{cases} \tag{7}$$

where $m=3$, which means shale permeability will rise about 3 orders of magnitude when rock fractured; k_0 is permeability of shale with no damage. ε_v is elastic strain.

The porosity evolution equation is [16]:

$$n_d = \begin{cases} 1-\dfrac{1-n_0}{\varepsilon_v}, \Omega = 0 \\ n_0 + 0.61\Omega^{3/2}, \Omega > 0 \end{cases} \tag{8}$$

where n_0 is porosity of shale with no damage.

NUMERICAL SIMULATION

Modelling

For the shale drilling at the depth of 3500 m in China western oilfield, the physical model is established by using porous media fluid-solid coupling unit (CPE4P) in software ABAQUS (Fig.1). By considering the disturbance damage and rock permeability changes during drilling, the stress distribution and influence of drilling fluid density is studied. The physical model parameters (Ⅰ) are indicated in Tab. 1. The parameter r_w is the borehole radius; ρ is the average density of rock; σ_H is the maximum horizontal ground stress; σ_h is the minimum horizontal ground stress; σ_v is the vertical ground stress; P_p is the pore pressure; P_i is the drilling fluid pressure; ρ_m is the drilling fluid density; η is the effective stress coefficient.

In boundary conditions setting process, the wall is permeable boundary and its displacement is unconstrained. The computational process is divided into three steps: (1) balance the initial stress field; (2) kill the borehole unit and load drilling fluid pressure; (3) calculate seepage-stress-damage coupling in 20 days.

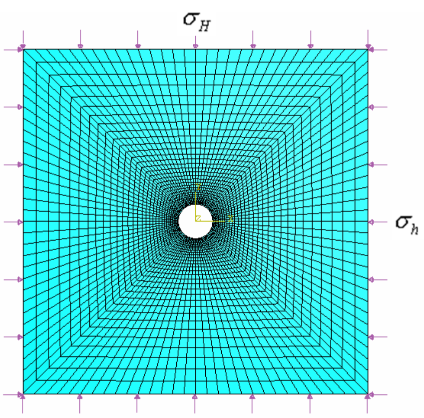

Figure 2: Finite element model.

ParameterⅠ	Value	ParameterⅠ	Value	parameterⅡ	Value	parameterⅡ	Value
H /m	3500	η	0.95	E / GPa	2	c_m / MPa	12
r_w / mm	158	ρ /(g/cm³)	2.13	μ	0.2	λ	0.2
σ_H / MPa	75	ρ_m /(g/cm³)	1.60	e	0.25		
σ_h / MPa	54	P_i / MPa	55	ϕ /°	25		
σ_v / MPa	70	P_p / MPa	45	k_0 / (m/s)	3×10^{-12}		

Table 1: Model parameters.

Setting mechanic parameters

The mechanic parameters (Ⅱ) of undamaged shale are shown in Tab. 1. The parameter E is the elastic modulus; μ is the Poisson ratio; e is the void ratio; λ is the harden parameter; c_m is the cohesion; ϕ is the frictional angle; k_0 is the permeability.

The mechanic parameters and hydraulic parameters of damaged rock is need to write in ABAQUS through software FORTRAN, which include $\bar{c}$, $\bar{E}$, k_d and n_d. Choose the equivalent plastic strain as damage variable and define the damage Ω is field variable according to Eq. (6). Define the $\bar{c}$, $\bar{E}$, k_d and n_d are state variables according to Eq. (2), (4), (7) and (8). It is too small to ignore the influence of damage on Poisson ratio.

RESULTS

When the drilling fluid ρ_m = 1.6 g/cm³, the damage distribution and permeability change of wall rock is calculated. Additionally, the distribution of pore pressure, stress and displacement is obtained.

- Damage and permeability. The distribution of damage is shown in Fig.3. In the non-uniform ground stress, most of wall rock is in elastic zone or protolith zone. The rock damage only occurred on the side of the minimum ground stress near the wall when ρ_m = 1.6 g/cm³. The maximum value of damage is 0.59 on the wall. The depth of damage rock is about $0.4\,r_w$ and the value of damage is decreasing with the increase of distance far from the wall.

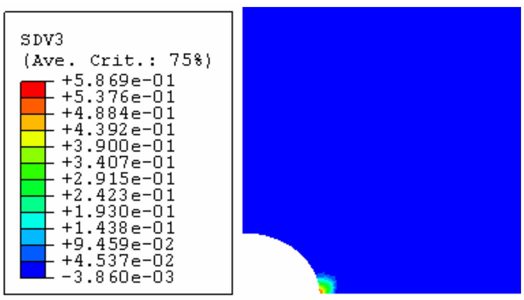

Figure 3: The distribution of damage.

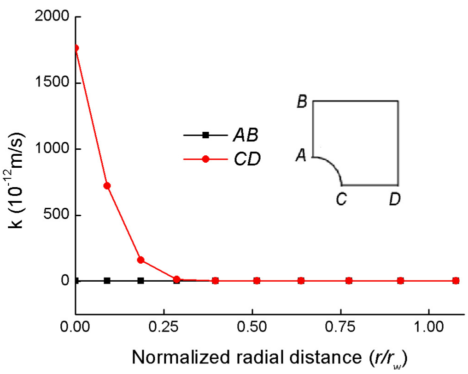

Figure 4: The distribution of permeability.

The permeability variation of rock is indicated in Fig.4. Compared with Fig.3, we can see that the distribution of permeability is corresponds with damage. The maximum permeability reach up to 1.76×10^{-9} m/s in damaged area. The permeability has no change in undamaged area.

- Equivalent plastic strain. The Fig.5 shows the influence of damage to equivalent plastic strain. The curves are plastic strain when existed damage or no, and existed damage but not consider the change of elastic modulus or permeability or cohesion. From the diagram we can see that the range of plastic area is always $0.4\,r_w$ which not changed in different conditions. But the maximum value of plastic strain will be affected by different conditions, especially the change of elastic modulus. For example, the maximum plastic strain will change from 0.04 to 0.15 if exists damage but not consider the change of elastic modulus.

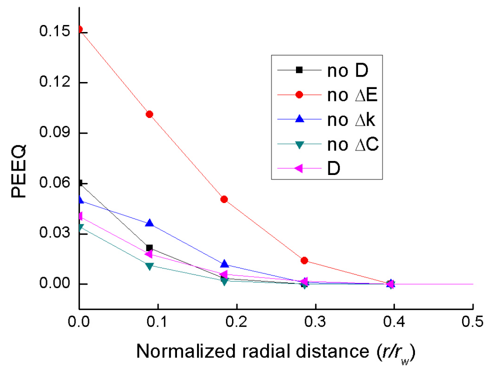

Figure 5: The influence of rock damage on plastic strain.

- Stress state: 20 days after drilling a borehole, the hoop stress (σ_θ) and radial stress (σ_r) in the direction of the minimum ground stress is indicated in Fig. 6(a). Radial stress on the wall is reduced rapidly owing to excavation. $0.4\,r_w$ far from the wall, there is the maximum hoop stress and the maximum difference between hoop stress and radial stress. So combined with Fig.3 we can find that there is shear damage in the range of $0.4\,r_w$ from the wall. Now, the wall rock is also stable through damaged. If the pressure of drilling fluid or pore pressure changed, however, the shear damage will changed correspondingly. Once the value of shear damage reached to its limit ($D_{\tau\max}$), the rock collapsed. Therefore, it is necessity to analyze the damage evolution and the distribution of stress in damaged area.

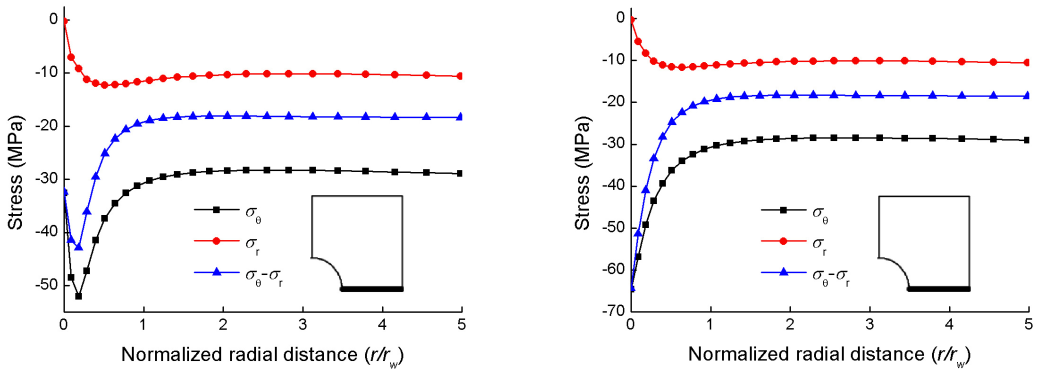

Figure 6. The distribution of hoop-radial stresses: (a) c_m =12 MPa; (b) c_m =50 MPa.

If the rock strength is very large (assume c_m =50 MPa), rock damage is not occur (Fig. 6(b)). There are only elastic zone and protolith zone in the wall rock. The maximum difference between hoop stress and radial stress is occurred on the wall. This means rock shear damage is appeared firstly on the wall, and then extended along the direction of the minimum ground stress. The rock collapse will be moved in a similar way.

- Displacement. Fig. 7 shows the rock displacement along the direction of the maximum and the minimum ground stress. The points in the direction of the maximum ground stress all moved toward the centre of borehole. The maximum displacement is 3.06 mm at the point on the wall, and it reduces gradually away from the borehole. The points in the direction of the minimum ground stress all moved deviate from the centre of borehole. The maximum displacement is 1.24 mm at the point $0.4\,r_w$ far from the wall.

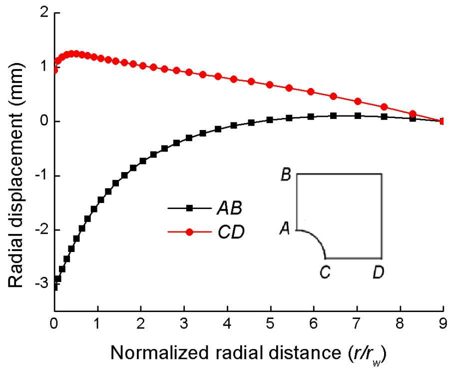

Figure 7: The distribution of displacements.

- Pore pressure. The distribution of pore pressure of well wall rock at different time after drilling is shown in Fig. 8. Due to the non-uniform ground stress, the maximum pore pressure is occurred at the direction of minimum horizontal ground stress, and the minimum pore pressure is occurred in the direction of maximum horizontal ground stress. With the passage of time, the pore pressure is dissipated gradually. After ten days, it tends to uniform in any direction. It is equal to the well fluid pressure at the well wall and to the initial pore pressure in the distance. It presents linear distribution between of them.

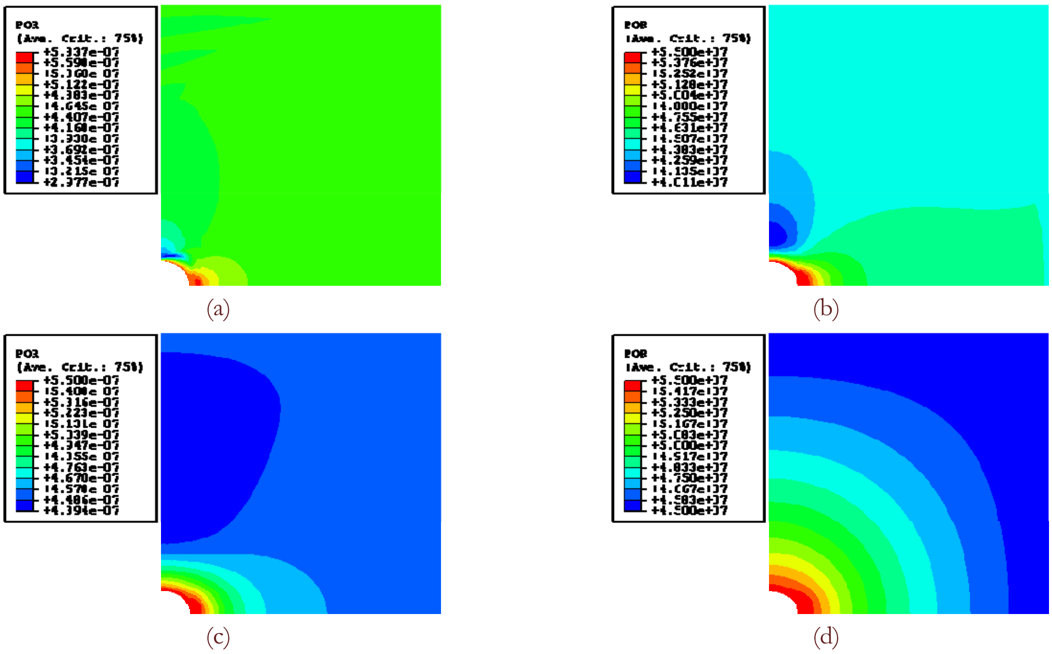

Figure 8: The pore pressure at different time (unit: Pa). (a) 100s; (b) 1h; (c) 10h; (d) 10d.

DIFFERENT DRILLING FLUID DENSITY

Fig. 9 shows the distribution of damage when ρ_m =1.98 g/cm^3. Both the direction of maximum and minimum ground stress exist damage near the wall. The range and value of damage in the direction of maximum ground stress are larger than the direction of minimum ground stress. The hoop stress (σ_θ) and radial stress (σ_r) in the direction of the maximum ground stress is indicated in Fig. 10. It is found that both hoop stress and radial stress are tensile stress. So there is a tensile damage in this direction. It can be deduced that the rock fracture when tensile damage reached to its limit ($D_{t\max}$).

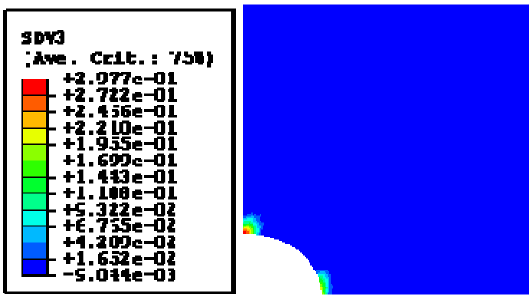

Figure 9: Damage when ρ_m =1.98g/cm^3.

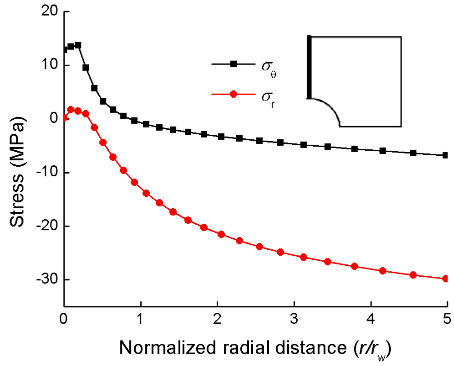

Figure 10: The hoop-radial stress.

When drilling fluid density changed from 1.4 g/cm^3 to 2.1 g/cm^3, the value and range of damage in the direction of maximum and minimum ground stress are analyzed in Figs. 11 and 12. With the increase of drilling fluid density, the maximum value (at node 2) and range of damage are decreased gradually in the direction of minimum ground stress. When drilling fluid density reached to 1.75 g/cm^3, the tensile damage occurred at node 1, and then increased gradually with its range in the direction of maximum ground stress.

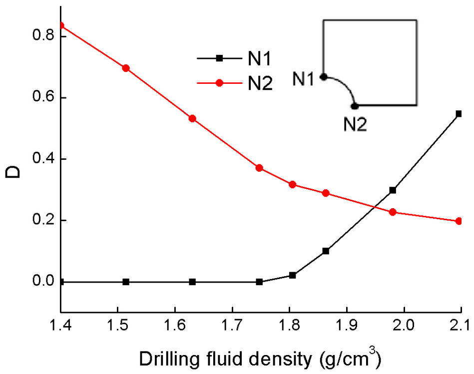

Figure 11: The value of damage at different drilling fluid density.

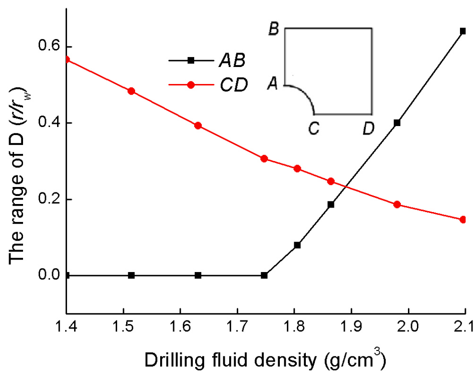

Figure 12: The range of damage at different drilling fluid density.

Therefore, if the drilling fluid density too low to produce the shear damage exceed its limit ($D_\tau \geq D_{\tau\max}$), the wall rock in the direction of minimum ground stress will be collapsed; if the drilling fluid density too high to produce the tensile damage exceed its limit ($D_t \geq D_{t\max}$), the wall rock in the direction of maximum ground stress will be fractured. The parameters $D_{\tau\max}$ and $D_{t\max}$ can be obtained by experiment. If the rock is brittle, there is $D_{\tau\max} = D_{t\max} = 0$. This means the damage zone in Figs. 3 and 9 would become a crushing zone.

CONCLUSIONS

According to a fluid-solid coupling theory, the concept of seepage coupled with plastic damage evolution is brought into Mohr-Coulomb failure criterion. The iterative calculation model of seepage-stress coupling which involving dynamic evolution of damage and permeability has been established.

For analyzing the practical drilling process, the physical model of borehole rock is built by using software ABAQUS. In the process of calculation, the change of elastic modulus, cohesion and permeability caused by rock damage is considered. The results include damage, permeability, stress, plastic strain, pore pressure and displacements.

The result shows that rock damage has a certain effect on plastic strain and stress distribution in plastic zone. The real and reliable result need to calculate using the coupled model which considered wall rock damage.

The drilling fluid density too high or too low will cause the tensile damage in the direction of maximum ground stress or the shear damage in the direction of minimum ground stress. If the damage exceeded its limit, the wall rock fractured or collapsed and a new shape borehole would be generated.
This study will improve the mechanical mechanism of borehole collapse and fracture, and provide a reference for the further research of seepage-stress-chemical-damage coupling of wall rock.

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