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Borehole stability analysis in oil and gas drilling in undrained condition

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Abstract. Borehole instability during drilling process occurs frequently when drilling through shale formation. When a borehole is drilled in shale formation, the low permeability leads to an undrained loading condition. The pore pressure in the compressed area near the borehole may be higher than the initial pore pressure. However, the excess pore pressure caused by stress concentration was not considered in traditional borehole stability models. In this study, the calculation model of excess pore pressure induced by drilling was obtained with the introduction of Henkel's excess pore pressure theory. Combined with Mohr-Coulumb strength criterion, the calculation model of collapse pressure of shale in undrained condition is obtained. Furthermore, the variation of excess pore pressure and effective stress on the borehole wall is analyzed, and the influence of Skempton's pore pressure parameter on collapse pressure is also analyzed. The excess pore pressure decreases with the increasing of drilling fluid density; the excess pore pressure and collapse pressure both increase with the increasing of Skempton's pore pressure parameter. The study results provide a reference for determining drilling fluid density when drilling in shale formation.

Keywords: borehole stability; collapse pressure; Mohr-Coulumb strength criterion; undrained; drilling fluid density; excess pore pressure

1. Introduction

Maintaining borehole stability is an important issue in oil and gas industry (Santarelli *et al*. 1986, Aadnoy 2003, Zoback *et al*. 2003, Al-Bazal *et al*. 2008). In the process of drilling, the economic losses caused by borehole instability reaches more than one billion dollar every year (Zeynal 2012), and the lost time is accounting for over 40% of all drilling related non-productive time (Zhang *et al*. 2009). It is also reported that shale account for 75% of all formations drilled by the oil and gas industry, and 90% borehole stability problems occur in shale formations (Ewy and Cook 1990, Mody and Hale 1993, Chen *et al*. 2003, Coelho *et al*. 2005). When a well is drilled, the formation around the borehole must sustain the load that was previously taken by the removed

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formation. As a result, an increase in stress around the borehole and stress concentration will be introduced (Zoback *et al*. 1985, Roegiers 2002). If the strength of the formation is not strong enough, the borehole will fail (Narayanasamy *et al*. 2009).Traditional models of borehole stability evaluation were mainly based on elastic mechanics (Bradley 1979, Santarelli *et al*. 1986, Aadnoy *et al*. 1987, Al-Ajmi and Zimmerman 2006), but in some cases the borehole remains stable even if the stress concentration around the borehole exceeds the strength of the formation, many scholars choose to use elastoplastic models for the analysis of borehole stability (Risnes and Bratli 1981, Roshan and Fahad 2012, Yan *et al*. 2013a, b).There are various chemicals in the drilling fluid which physically and chemically interact with shale formations. On one hand, these interactions will result in the generationof swelling stress (Chenevert and Pernot 1998, Tan *et al*. 1998). On the other hand, it alleviates the mechanical strength of the borehole wall rock (Chenevert 1970, Chen 2001, Yan *et al*. 2013b). Chemical effect of drilling fluid on shale stability was evaluated by many scholars (Simpson and Dearing 1989, Hale and Mody 1992, Van Oort *et al*. 1995, Tan *et al*. 2002, Yan *et al*. 2013b).

In deep buried shale, the formation fluids are trapped in pore spaces (Chen and Ewy 2002). Because the native permeability of shale is very low, and a tight layer of mud cake will generate on the borehole wall which can prevent the seepage of the fluid between the borehole and the formation, rock deformation is under an undrained condition. In contrast, for highly permeable reservoirs, fluid can be drained from the pore space subjected to applied loadings, so the deformation of permeable rock is governed by the drained elastic modulus (Detournay and Cheng 1993). Because the native permeability of shale is on the order of nanodarcy ($1–10^3$ nd), the communication of fluids in shale is not easy. When a borehole is drilled in shale formation, the low permeability leads to an undrained loading condition (Cui *et al*. 1999). The pore pressure in the compressed area near the borehole may be higher than the initial pore pressure. However, traditional borehole stability models treated drilling in shale as drained process, and the pore pressure changing caused by stress concentration was not taken into consideration. Excess pore pressure theory (Hu 1997) in soil mechanics will be adopted in this paper, combined with Mohr-Coulumb strength criterion to research the collapse pressure in shale.

2. Excess pore pressure

Shale formation is composed of solid particle skeleton and pores are full of fluid. When imposed by an external force, the force will be balanced by both pore pressure and effective stress. Drilling will result in stress concentration around the borehole, under the undrained condition, part of the stress will be taken by the pore fluid, so the pore pressure will change after drilling. The pore pressure increment induced by external load is called "excess pore pressure" (Hu 1997), marked with ΔP and expressed in the following equation.

$$\Delta P = P_p - P_{p0} \tag{1}$$

where ΔP is the excess pore pressure; P_p is the pore pressure after drilling; P_{p0} is the initial pore pressure.

At present, the solution of excess pore pressure is based on the research of Skempton and Henkel (Gong 1996). Skempton (1954) established the calculation formula of excess pore pressure based on the experimental research of conventional triaxial tests.

$$\Delta P = B[\Delta\sigma_3 + A(\Delta\sigma_1 - \Delta\sigma_3)] \tag{2}$$

where B is the Skempton's pore pressure parameter under the acting of isotropic stress and deviatoric stress both,and it is related to the formation saturation, for saturated formation, $B = 1.0$; A is the Skempton's pore pressure parameterunder the acting of deviatoric stress, which can be determined by experiment or experience; $\Delta\sigma_1$ and $\Delta\sigma_3$ stands for the maximum and the minimum principal stress increment respectively.

Henkel (1960) reasoned that under complex stress condition, the calculation of excess pore pressure should take the influence of the intermediate principle stress into consideration. The excess pore pressure under triaxial stress condition consists of two parts: one part caused by mean normal stress and the other part caused by mean shear stress. He put forward the following calculation formulas

$$\Delta P = \beta\Delta\sigma_{oct} + \gamma\Delta\tau_{oct} \tag{3}$$

In which

$$\Delta\sigma_{oct} = \frac{1}{3}(\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3) \tag{4}$$

$$\Delta\tau_{oct} = \frac{1}{3}\sqrt{(\Delta\sigma_1 - \Delta\sigma_2)^2 + (\Delta\sigma_2 - \Delta\sigma_3)^2 + (\Delta\sigma_3 - \Delta\sigma_1)^2} \tag{5}$$

where γ and β are the Henkel's pore pressure coefficients. For saturated formation, $\beta = 1$.

In conventional triaxial tests, $\Delta\sigma_2 = \Delta\sigma_3$. Introduce it to the Henkel's excess pore pressure formula, the following formula is available

$$\Delta P = \Delta\sigma_3 + (1 + \sqrt{2})(\Delta\sigma_1 - \Delta\sigma_3)/3 \tag{6}$$

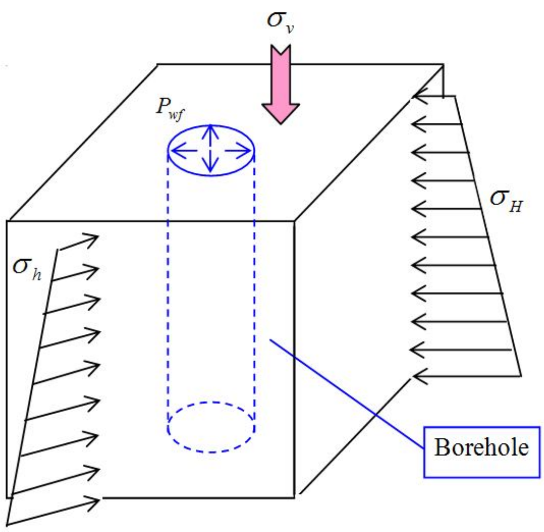


Fig. 1 Mechanical calculation model

Compared with Skempton's formula, Henkel's excess pore pressure formula can be rewritten as following

$$\Delta P = \beta \Delta \sigma_{oct} + (3A-1)\Delta \tau_{oct} \big/ \sqrt{2} \approx \beta \Delta \sigma_{oct} + (2.12A - 0.71)\Delta \tau_{oct} \tag{7}$$

3. Borehole stability model in undrained condition

The in-situ stress has been existed in the formation before a well is drilled. After drilling, borehole fluid pressure replaces the rock and provides support, and the stress around the borehole will be redistributed (Lu and Tang 2000). Assuming the formation around the borehole is porous elastic medium (Aadnoy *et al*. 1987, Sone and Zoback 2013, Zhu *et al*. 2014, Yan *et al*. 2014), so the stress distribution can be obtained using the following mechanical model. In an infinite plane, a circular hole with uniform internal pressure is under the effect of two horizontal stresses in the plane of the infinity, and under the effect of overburden pressure in the vertical direction, as shown in Fig. 1. The shear failure of the borehole appears on the borehole wall (Fjær *et al*. 2008, Chen *et al*. 2008). The borehole stress for a vertical well is as follows (Chen *et al*. 2008)

$$\begin{cases} \sigma_r = \dfrac{R^2}{r^2} P_{wf} + \dfrac{(\sigma_H + \sigma_h)}{2}\left(1 - \dfrac{R^2}{r^2}\right) + \dfrac{(\sigma_H - \sigma_h)}{2}\left(1 + \dfrac{3R^4}{r^4} - \dfrac{4R^2}{r^2}\right)\cos 2\theta \\ \sigma_\theta = -\dfrac{R^2}{r^2} P_{wf} + \dfrac{(\sigma_H + \sigma_h)}{2}\left(1 + \dfrac{R^2}{r^2}\right) - \dfrac{(\sigma_H - \sigma_h)}{2}\left(1 + \dfrac{3R^2}{r^4}\right)\cos 2\theta \\ \sigma_z = \sigma_v - \mu\left[2(\sigma_H - \sigma_h)\left(\dfrac{R}{r}\right)^2 \cos 2\theta\right] \\ \tau_{r\theta} = \dfrac{(\sigma_H - \sigma_h)}{2}\left(1 - \dfrac{3R^2}{r^4} + \dfrac{2R^2}{r^2}\right)\sin 2\theta \end{cases} \tag{8}$$

were σ_r, σ_θ and σ_z are the radial stress, effective tangential stress and effective axial stress around the borehole, respectively; $\tau_{r\theta}$ is the shear stress; R is the radius of the borehole wall; r is the distance to the axial of the borehole; σ_v is the overburden pressure; σ_H and σ_h are the maximum and minimum horizontal stresses, respectively; P_{wf} is the fluid column pressure; θ is well around angle (defined starting at a point on the borehole to the maximum horizontal stress direction); μ is the Poisson's ratio.

The stress state around a borehole is shown in Fig. 2. The used calculation parameters are shown in Table 1. In drilling process, when the drilling fluid density is low, shear failure may occur around the borehole, and then cause borehole collapse. The shear failure is induced by the difference of tangential stress and radial stress (Bell and Gough 1979, Haimson and Chang 2002). We can know from Fig. 2, the stress differential ($\sigma_\theta - \sigma_r$) on the borehole wall is higher than inside the formation. And there is no shear stress on the borehole wall. So Shear failure is determined by stress differential ($\sigma_\theta - \sigma_r$) on the borehole wall, ($\sigma_\theta - \sigma_r$) reaches its maximum when $\theta = \dfrac{\pi}{2}$ or $\dfrac{3\pi}{2}$. If the stress differential surpasses the shear strength of the formation, borehole collapse will occur and form borehole caving elliptical. The collapse occurs at the minimum horizontal stress direction

(Zoback *et al*. 1985, Haimson and Chang 2002, Fjær *et al*. 2008, Yan *et al*. 2013b). When $\theta = \frac{\pi}{2}$ or $\frac{3\pi}{2}$, the stresses at the two points can be written as following

$$\begin{cases} \sigma_r = P_{wf} \\ \sigma_\theta = -P_{wf} + 3\sigma_H - \sigma_h \\ \sigma_z = \sigma_v + 2\mu(\sigma_H - \sigma_h) \end{cases} \tag{9}$$

The principle stress increment induced by drilling is expressed as following

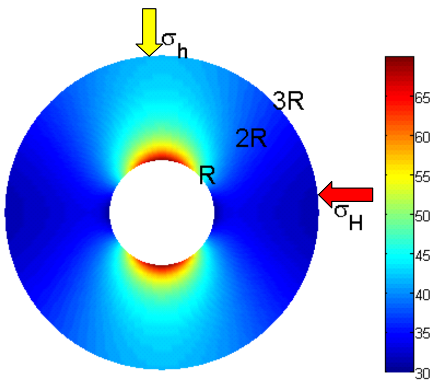
$$\begin{cases} \Delta\sigma_r = \sigma_r - \sigma_h = P_{wf} - \sigma_h \\ \Delta\sigma_\theta = \sigma_\theta - \sigma_H = -P_{wf} + 2\sigma_H - \sigma_h \\ \Delta\sigma_z = \sigma_z - \sigma_v = 2\mu(\sigma_H - \sigma_h) \end{cases} \tag{10}$$

Calculating the mean normal stress increment $\Delta\sigma_{oct}$ and the mean shear stress increment $\Delta\tau_{oct}$ based on Eq. (10)

$$\Delta\sigma_{oct} = \frac{2+2\mu}{3}(\sigma_H - \sigma_h) \tag{11}$$

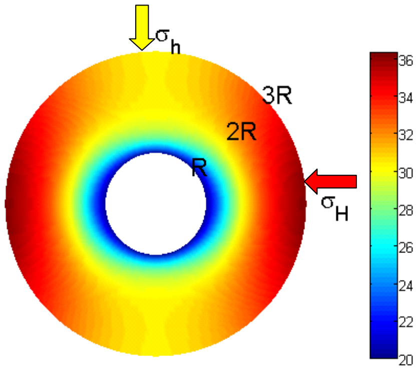
Table 1 Calculation parameters

Maximum horizontal stress	40 MPa
Minimum horizontal stress	30 MPa
Overburden pressure	45 MPa
Pore pressure	20 MPa
Poisson’s ratio	0.25

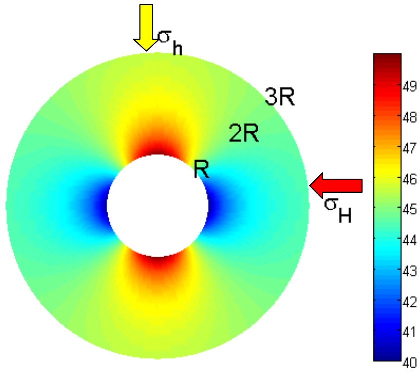


(a) Tangential stress

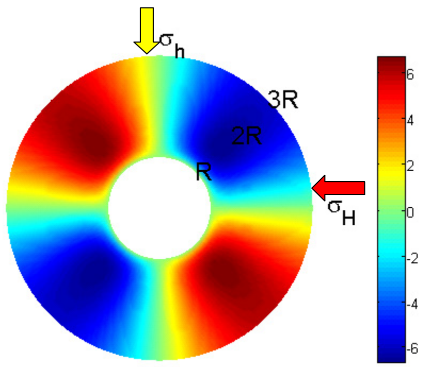
Fig. 2 Stress state on the surrounding rock of a vertical well



(b) Radial stress



(c) Verticalstress



(d) Shear stress

Fig. 2 Stress state on the surrounding rock of a vertical well

$$\Delta\tau_{oct} = \frac{1}{3}\sqrt{4(P_{wf}-\sigma_H)^2 + \left[P_{wf}-(1-2\mu)\sigma_h - 2\mu\sigma_H\right]^2 + \left[P_{wf}+(1-2\mu)\sigma_h-(2-2\mu)\sigma_H\right]^2} \quad (12)$$

Inserting $\Delta\sigma_{oct}$ and $\Delta\tau_{oct}$ into Eq. (7), the excess pore pressure will be obtained by Henkel's excess pore pressure formula

$$\Delta P = \frac{2+2\mu}{3}(\sigma_H - \sigma_h) + \frac{1}{3}(2.12A - 0.71)M \tag{13}$$

In which

$$M = \sqrt{4(P_{wf} - \sigma_H)^2 + \left[P_{wf} - (1-2\mu)\sigma_h - 2\mu\sigma_H\right]^2 + \left[P_{wf} + (1-2\mu)\sigma_h - (2-2\mu)\sigma_H\right]^2} \tag{14}$$

The effective stress can be written as following

$$\begin{cases} \sigma_r' = P_{wf} - \alpha\left[P_{P0} + \frac{2+2\mu}{3}(\sigma_H - \sigma_h) + \frac{1}{3}(2.12A - 0.71)M\right] \\ \sigma_\theta' = -P_{wf} + 3\sigma_H - \sigma_h - \alpha\left[P_{P0} + \frac{2+2\mu}{3}(\sigma_H - \sigma_h) + \frac{1}{3}(2.12A - 0.71)M\right] \\ \sigma_z' = \sigma_v + 2\mu(\sigma_H - \sigma_h) - \alpha\left[P_{P0} + \frac{2+2\mu}{3}(\sigma_H - \sigma_h) + \frac{1}{3}(2.12A - 0.71)M\right] \end{cases} \tag{15}$$

where, α is Biot's coefficient.

Shear failure of the borehole is subject to the Mohr-Coulumb strength criterion. Shear failure will occur when the Mohr's circle constituted by the maximum and minimum effective principal stress on the borehole wall exceeds the failure strength. The Mohr-Coulumb strength criterion expressed by principal stress is as following (Fjær *et al*. 2008)

$$\sigma_1 - \sigma_3 \tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) - 2C\tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) = 0 \tag{16}$$

where, σ_1 and σ_3 are the maximum and minimum effective principal stress; φ is the internal friction angel; C is the cohesive force.

When the Mohr's circle constructed by radial and tangential effective stress reaches the rock strength, shear failure will occur on the borehole wall (Morita *et al*. 1989, Fjær *et al*. 2008, Chen *et al*. 2008). When shear failure occurs, the stress state on the borehole wall can be written as

Table 2 Calculation parameters

Maximum horizontal stress	40 MPa
Minimum horizontal stress	30 MPa
Overburden pressure	45 MPa
Pore pressure	20 MPa
Poisson's ratio	0.25
A	0.5
Biot's coefficient	0.6
Internal friction angel	30°
Cohesive force	5 MPa

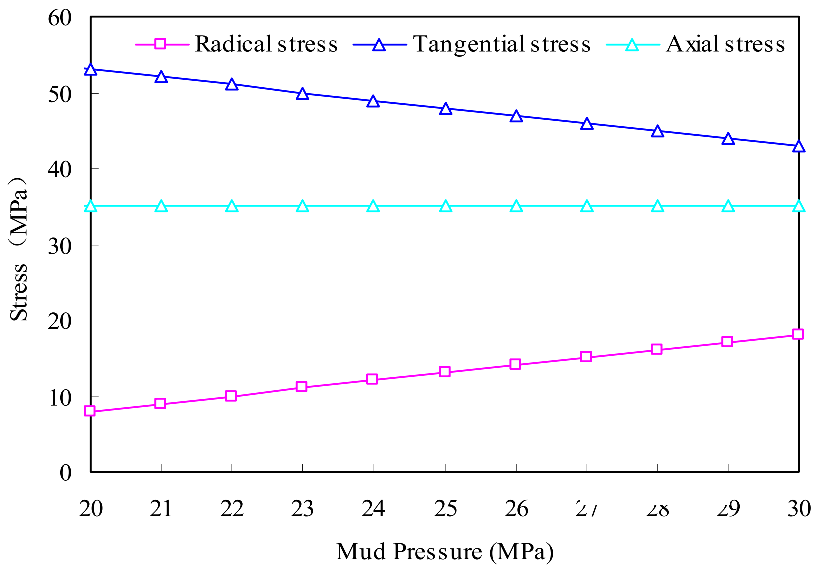


Fig. 3 Total stress in the minimum stress direction versus drilling fluid pressure

following

$$\begin{cases} \sigma_1 = -P_{wf} + 3\sigma_H - \sigma_h - \alpha\left[P_{P0} + \dfrac{2+2\mu}{3}(\sigma_H - \sigma_h) + \dfrac{1}{3}(2.12A - 0.71)M\right] \\ \sigma_2 = \sigma_v + 2\mu(\sigma_H - \sigma_h) - \alpha\left[P_{P0} + \dfrac{2+2\mu}{3}(\sigma_H - \sigma_h) + \dfrac{1}{3}(2.12A - 0.71)M\right] \\ \sigma_3 = P_{wf} - \alpha\left[P_{P0} + \dfrac{2+2\mu}{3}(\sigma_H - \sigma_h) + \dfrac{1}{3}(2.12A - 0.71)M\right] \end{cases} \tag{17}$$

Introduce Eq. (17) into Eq. (16), the collapse pressure can be calculated by Eq. (18)

$$\begin{aligned} f(P_{wf}) = &\left[1 + \tan^2\left(45^\circ + \frac{\phi}{2}\right)\right]P_{wf} - 3\sigma_H + \sigma_h + 2C\tan^2\left(45^\circ + \frac{\phi}{2}\right) \\ &+ \alpha\left[1 - \tan^2\left(45^\circ + \frac{\phi}{2}\right)\right]\left[P_{P0} + \frac{2+2\mu}{3}(\sigma_H - \sigma_h) + \frac{1}{3}(2.12A - 0.71)M\right] = 0 \end{aligned} \tag{18}$$

4. Analysis

To research the variation rule of the collapse pressure and stress on the borehole wall, we took a sit of formation parameters to analyze. The calculation parameters are shown in Table 1.

Fig. 3 shows the total stress on the borehole wall versus mud pressure (drilling fluid density). From the figure we can see that the radical stress increase with the increase of mud pressure. The tangential stress decreases with the mud pressure. And the axial stress do not change when the

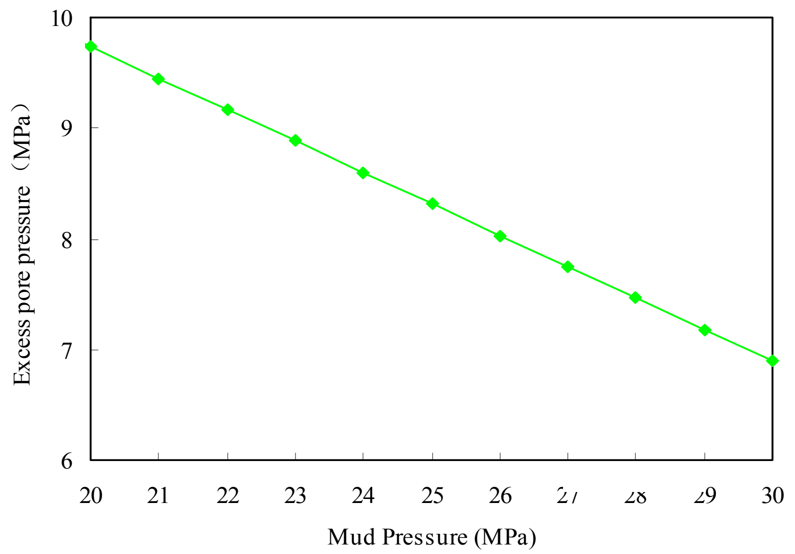


Fig. 4 Excess pore pressure and effective stress versus mud pressure

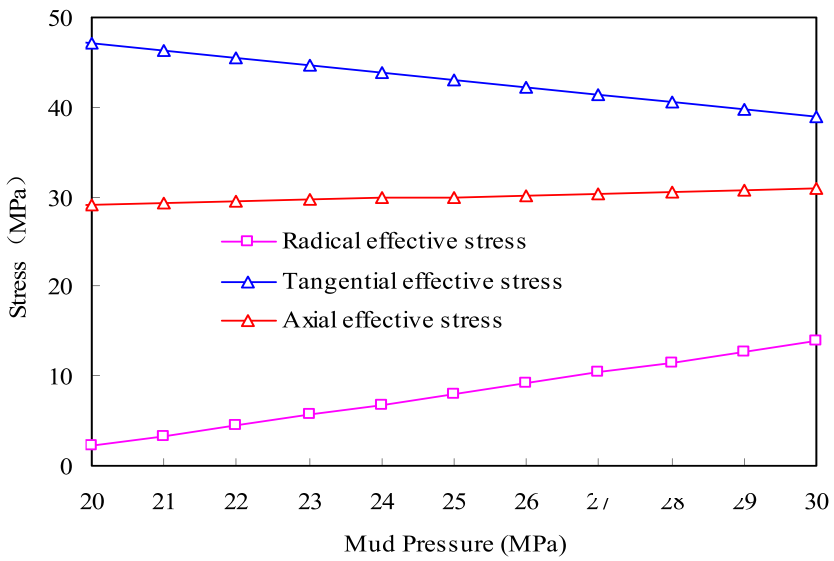


Fig. 5 Effective stress versus mud pressure

mud pressure changing.

Figs. 4 and 5 show the change rule of excess pore pressure and effective stress on the borehole wall versus mud pressure (drilling fluid density). It reveals that higher drilling fluid density means a smaller excess pore pressure. That is because with the increase of drilling fluid density, the mud pressure to support the borehole wall increases, stress concentration decreases, so the excess pore pressure decreases. The tangential effective stress decreases with the increasing of the borehole pressure. The radical effective stress and axial effective stress both increase with the increasing of

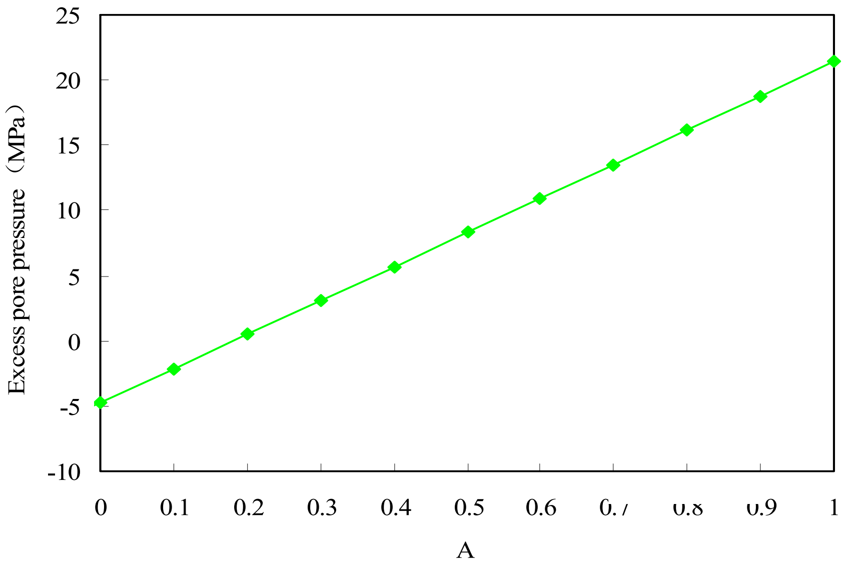


Fig. 6 Excess pore pressure versus Skempton's pore pressure parameter "A"

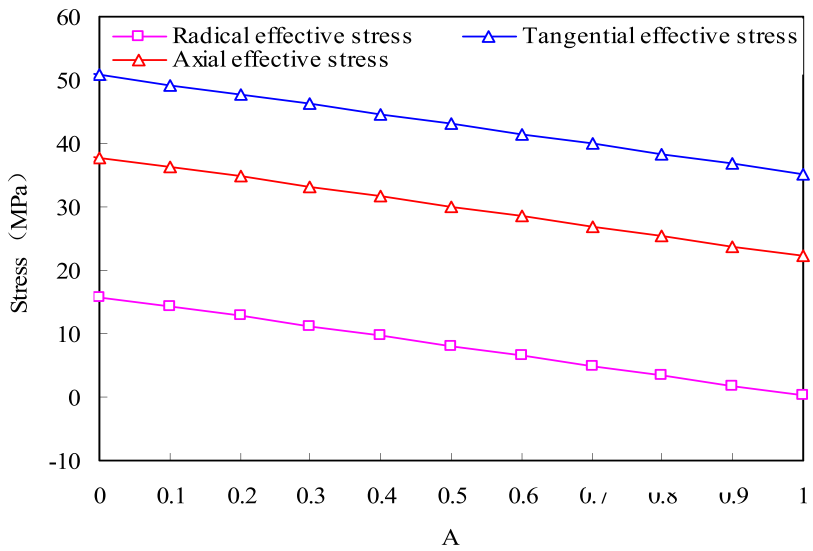


Fig. 7 Effective stress versus Skempton's pore pressure parameter "A"

mud pressure.

Figs. 6 and 7 shows the change rule of excess pore pressure and effective stress on the borehole wall versus Skempton's pore pressure parameter "A". The excess pore pressure increases with the increasing of "A". The tangential effective stress, radical effective stress and axial effective stress all decrease with the increasing of "A". A higher Skempton's pore pressure parameter means more external force will be balanced by pore pressure, so the excess pore pressure will increase, while the effective stress decrease.

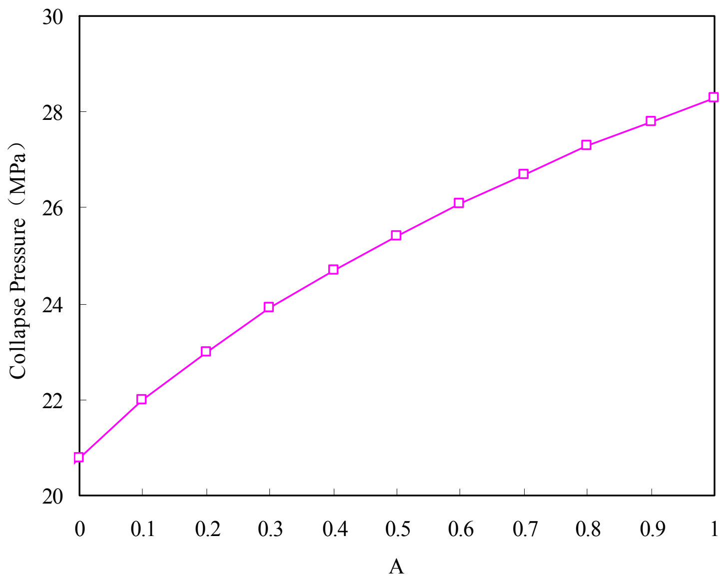


Fig. 8 Collapse pressure versus Skempton's pore pressure parameter "A"

Fig. 8 shows the change rule of collapse pressure versus Skempton's pore pressure parameter "A". It is obvious that the collapse pressure increases nonlinearly with the increasing of coefficient "A". That is because the pore pressure increases with the increase of "A", the effective support of the drilling fluid to the borehole wall decreases, which caused the borehole prone to collapse. When $A = 1$, the collapse pressure increases by approximate 36% compared with the value when $A = 0$. The excess pore pressure has a big effect on the collapse pressure, it should not be ignored when determining the collapse pressure.

5. Case study

Rock mechanical parameters were calculated using logging data. The prediction model of uniaxial compressive strength (UCS) can be expressed as (Zhu *et al*. 2012)

$$\text{UCS} = f_1 E(1 - V_{cl}) + f_2 E V_{cl} \tag{19}$$

where: E is the Young's modulus; V_{cl} is the clay mineral content; f_1 and f_2 are coefficients.

Overburden pressure can be obtained by integrating of logging density, as for sea-drilling water depth should be considered (Chen *et al*. 2008)

$$\sigma_V = \int_0^{H_1} \rho_w g dh + \int_{H_1}^{H_2} \rho_r g dh \tag{20}$$

where σ_V is the overburden pressure; H_1 is the water depth; H_2 is the depth below sea level; ρ_w is the seawater density; ρ_r is the formation density; g is the gravity acceleration.

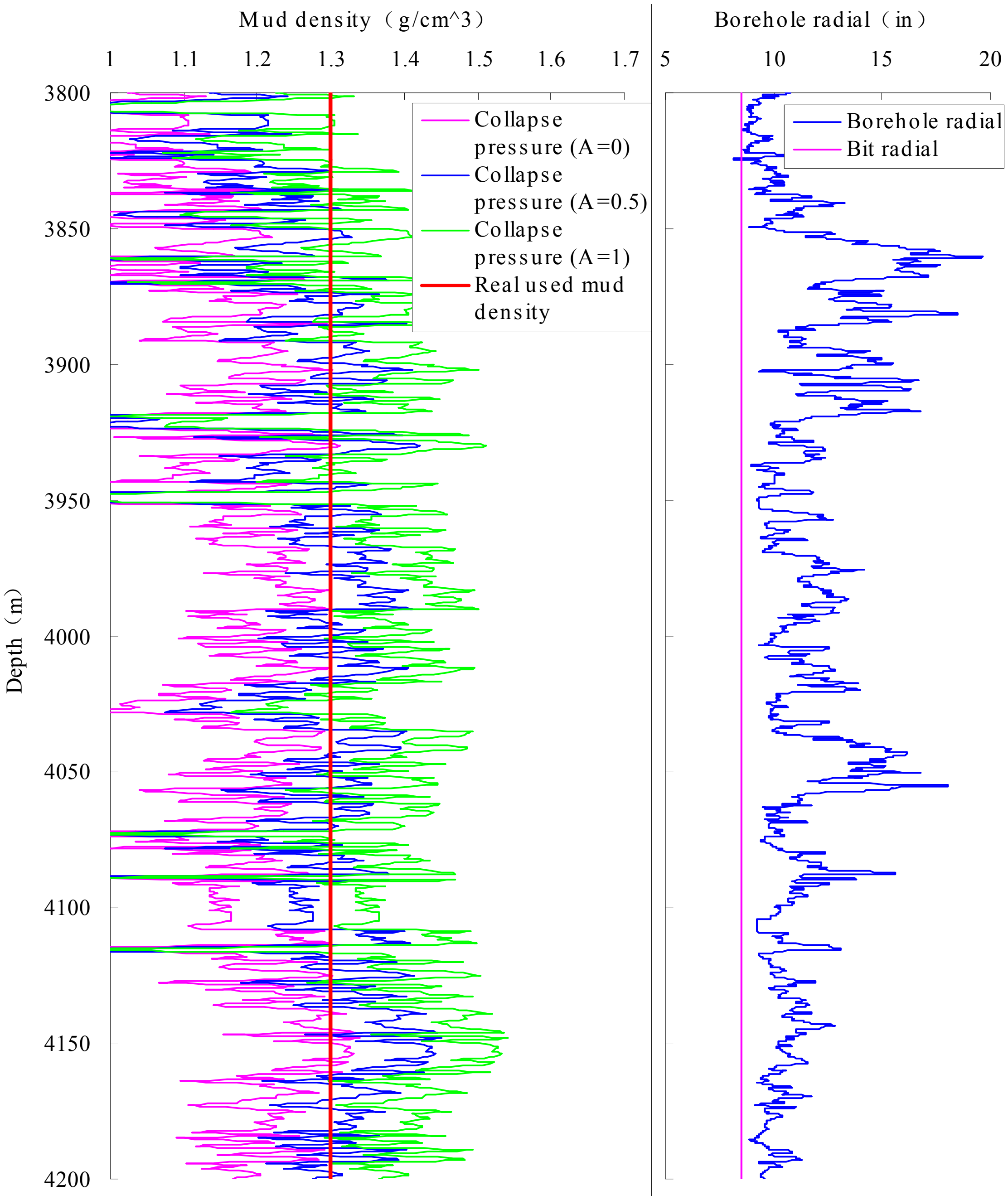


Fig. 9 Collapse pressure of Bohai Bay

The horizontal in-situ stress mainly comes from the weight of overlying formation and the tectonic stress, the calculation model of non-uniform in-situ stress using two tectonic stress coefficients is as following (Chen *et al*. 2008)

$$\begin{cases} \sigma_H = \left(\dfrac{\mu_s}{1-\mu_s} + \omega_1 \right)\left(\sigma_V - \alpha P_p\right) + \alpha P_p \\ \sigma_h = \left(\dfrac{\mu_s}{1-\mu_s} + \omega_2 \right)\left(\sigma_V - \alpha P_p\right) + \alpha P_p \end{cases} \tag{21}$$

where μ_s is the static Poisson's ratio; ω_1 and ω_2 is the horizontal tectonic stress coefficients in two directions.

There is a giant thick section of shale in Paleogene Dongying Formation and Shahejie Formation in Bohai Bay. .and they are brown gray shale with pure quality and soft to middle hardness. Fig. 9 shows the collapse pressure of a well in Bohai Bay. The collapse pressure is higher when considering the excess pore pressure (A > 0) than the collapse pressure not considering the excess pore pressure (A = 0). The real used mud density in drilling is higher than the collapse pressure calculated by traditional model, but is smaller than the collapse pressure calculated by the model proposed in this paper. Complex accidents such as wellbore collapses, stuck pipe, pump suffocation, reaming, back reaming were very frequently while drilling, and the borehole enlargement reached more than 100% of this well.

6. Conclusions

When a borehole is drilled in shale formation, the low permeability leads to an undrained loading condition. The variation in volumetric strain caused by stress concentration will result in an increase of the pore pressure, then the excess pore pressure generates.

With the increase of drilling fluid density, the borehole pressure to support the borehole wall increases, stress concentration decreases, the excess pore pressure decreases. The tangential effective stress decreases with the increasing of the borehole pressure. The radical stress and axial stress increase with the increasing of borehole pressure.

The excess pore pressure increases with the increasing of Skempton's pore pressure parameter "A". The tangential effective stress, radical effective stress and axial effective stress all decrease with the increasing of "A".

Excess pore press theory is firstly used in the calculation model of collapse pressure in oil and gas drilling. The excess pore pressure will decrease the support of drilling fluid on borehole wall and caused the increasing of collapse pressure. The collapse pressure increases nonlinearly with the increasing of coefficient "A". The excess pore pressure has a big effect on the collapse pressure, it should not be ignored when determine the collapse pressure of oil and gas drilling.

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