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Study of the Influence of Rock Mechanical Parameters on the Wellbore Stability under Depleted Reservoir Condition

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Abstract **-** The scarcity of oil and gas reserves have pushed drilling companies to conduct drilling operations in mature oilfields. However, drilling in brownfield can lead to several hazards such as loss circulation and wellbore collapse due to the reservoir pore pressure decline. In this research, wellbore stability of directional wells in depleted reservoirs is analyzed purposely to enhance wellbore integrity during drilling operations. Experimental tests are first of all conducted to investigate the effect of pore pressure depletion on the rock formation mechanical parameters such as compression strength, Young's modulus, Poisson's ratio. Then, analytical equations of transformations matrices are used to transform in-situ stress after reservoir depletion from the in-situ coordinate system to the wellbore coordinate system. Finally, the wellbore collapse gradient and fracture gradient under different pore pressure condition are evaluated using Mohr-coulomb shear failure and tensile failure criteria. The results showed that the formation strength after pressure decline is also a main factor contributing to the reduction of the mud density window. The safe mud window narrowed with the pore pressure depletion, for the inclination angle of 90° the initial mud window in the direction of the minimum horizontal stress reduced by 52.80% after reservoir depletion while it reduced by 85.78% in the maximal horizontal stress direction. The novelty of the current research lies in the fact that the model accurately accounts the effect of the reservoir depletion on the rock elastic parameters during the wellbore stability analysis which is an aspect that has been rarely discussed in the previous publications.

Keywords**:** Rock mechanical parameters, wellbore stability, directional wells, depleted reservoir

1. Introduction

More than 70% of oil and gas production comes from secondary or tertiary development. With the progressive oil and gas production, the reservoir pore pressure declines and affects the in-situ stress and the rock formation parameters, finally resulting into complex accidents such as wellbore collapse and wellbore fracturing. Several researchers have conducted wellbore stability studies of directional wells under depleted reservoir condition:

Geertsma (1957) were among the first researchers to study the effect of pore pressure decline on volumetric changes of porous rocks. They concluded that the rock will deform after the reservoir pressure depletion. Later, (Ge, Qu and Huang, 1994) investigated the relationship between the minimum horizontal principal stress and the formation pore pressure decline and established a calculation model for fracture pressure in vertical wells after pressure depletion; Addis (1997) equally investigated the effect of reservoir depletion on wellbore stability and established a linear positive correlation between the minimum horizontal stress and the pressure change of the pressure-depleted formation. Additionally, (Liang, Wen, Wang, Zhang, Cheng and Zhao, 2004) studied the effects of pore pressure alteration on the in-situ stress and demonstrated that the fracture pressure decreased with the pore pressure in different hydrocarbon fracture workovers. (Schutjens, Kuvshinov, Dunayevsky, Rambow, Fehler, Khodaverdian, Frazer and Leeftink, 2007) utilized an analytical model to describe the wellbore stress change due to drawdown and depletion and demonstrated that the total stress is maximal along the wellbore axis and is minimal in the direction orthogonal to the wellbore. (Holt and Horsrud, 2008) investigated the stability of wellbore under depleted condition and established the difference between the in-situ stress variation and the pore pressure decline.

Furthermore, (Tan, He, Chen, Lu and Fang, 2010) investigated the wellbore stability of directional wells in depleted reservoirs in a low permeability and fractured reservoir with high heterogeneity. They conducted numerical simulations to model the wellbore stability problem and their results demonstrated that the leakage should be prevented when drilling in pressure depleted formation and highly deviated wells. (Guan, Xie, Tan, Deng , Fang and Zhao, 2012) conducted wellbore stability research in ultra-low pressure horizontal wells of Yacheng 13-1 gas field and demonstrated that collapse pressure and fracture pressure are reduced to different degrees due to formation pressure depletion. Moreover, (Yan, Deng, Wei, Tan, Deng and Hu, 2013) evaluated the stability of pressure depleted reservoirs by investigating the influence of pressure depletion on reservoir in-situ stress and stress distribution around the wellbore. Their results showed that there is a neutral angle in depleted reservoir drilling; when the neutral angle is higher than the inclination angle, the mud window will become wider, and when the inclination angle is greater than the neutral angle, the mud window will become narrower. More recently, Li and Gray (2015) analyzed the influence of reservoir pore pressure decline on the maximum and minimum horizontal principal in-situ stress and established a wellbore stability model of deviated wells in depleted reservoir.

Despite some studies have been conducted in the past to investigate the stability of directional wells under depleted condition, most of these studies mainly investigated the effect of pore pressure decline on the in-situ stress assuming the rock mechanics parameters remain constant under reservoir depletion (Ge, Qu and Huang, 1994; Addis, 1997; Liang, Wen, Wang, Zhang, Cheng and Zhao, 2004; Yan, Deng, Wei, Tan, Deng and Hu, 2013; Li and Gray, 2015). However, practice has proved that pressure depletion does not only affect the in-situ stress, but equally strongly influences the rock mechanical properties (Geertsma, 1973; Zhang, Bao and Lu, 2002; Liu, Shen, Liang, Lin and Liu, 2011). Therefore, the effect of formation pore pressure decline on the rock formation parameters should be comprehensively considered during the wellbore stability analysis of depleted reservoirs.

Due to the previously aforementioned reasons, this paper investigates the wellbore stability of deviated wellbores under depletion condition for a gas field reservoir in Yinggehai Basin by considering the effect of the pore pressure decline on the rock formation mechanical parameters. Experiment tests under different pore pressure conditions were first conducted to determine the effect of pore pressure depletion on the rock mechanical parameters (compressive strength ,elastic modulus, Poisson's ratio, tensile strength); Then, Python programming was established to compute the stress distribution around the wellbore by using the generalized Hooke's law, finally the safe mud window of deviated wellbore under depleted condition was elaborated by application of the Mohr Coulomb criterion.

2. Statement of theory and definition

The stability of deviated wellbores in depleted reservoirs is a complex issue which includes the following steps:

1. Rock mechanics experiments under depleted reservoir condition;
2. Stress distribution around the wellbore after reservoir depletion ;
3. Safe mud window determination of deviated wellbores in depleted reservoirs.

2.1. Rock mechanics experiments under depleted reservoir condition

The main objective in this part is to determine the variation law of sandstone rock mechanical parameters (compressive strength, tensile strength, elastic modulus and poisson's ratio) under different pore pressure condition. The sandstone rock samples were taken from a reservoir in a gas field in the Yinggehai Basin and processed into cylinders with a diameter of 25 mm and an aspect ratio of 1.8-2.0 shaped core. The rock strength experiment was carried out with a TAW-2000 microcomputer-controlled electro-hydraulic servo rock triaxial testing machine as shown in Fig. 1.

A specific dispositive was mounted on the triaxial testing machine to model the pore pressure reduction due to reservoir depletion as it can be seen in Figs. 2-3. As presented in Fig. 4, the lower part of the dispositive comports an inlet pore pressure tube which is connected to a pump that provides fluid pressure inside the system. The pump pressure is designed to be equal to the reservoir pore pressure. The fluid from the inlet pore pressure tube passes through the pores of the rock sample and finally flows back outside the sample from the outlet pore pressure tube.

Fig. 1 TAW-2000 microcomputer-controlled electro-hydraulic servo rock triaxial testing machine.

Fig. 2. Mounting the rock sample on the dispositive.

Fig. 3. Fixing the pore pressure reduction device on the rock triaxial testing machine

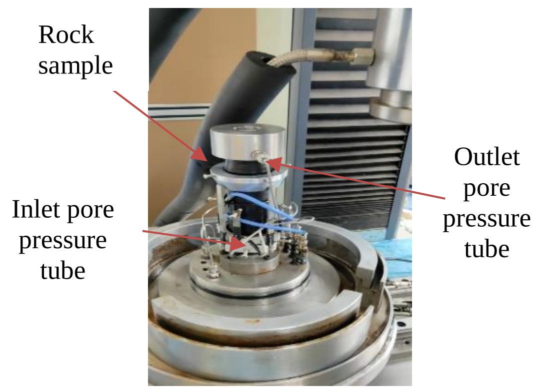

Fig. 4. Experimental modeling of the reservoir depletion

2.2. In-situ stress determination after reservoir depletion

The current research assumes that the gravity and the tectonic geological forces are the main forces which generate in-situ stress. The in-situ stress after reservoir depletion are expressed as (Li and Gray, 2010):

$$\sigma_H = \left(\frac{\mu}{1-\mu} + \omega_1\right)\left(\sigma_v - \alpha P_p\right) + \alpha P_p - \frac{1-2\mu}{1-\mu}\alpha\left(P_{f\,initial} - P_{f\,depletion}\right) \quad (1)$$

$$\sigma_h = \left(\frac{\mu}{1-\mu} + \omega_2\right)\left(\sigma_v - \alpha P_p\right) + \alpha P_p - \frac{1-2\mu}{1-\mu}\alpha\left(P_{f\,initial} - P_{f\,depletion}\right) \quad (2)$$

where, σ_H and σ_h are respectively the in-situ stress after reservoir depletion in the maximum and minimum horizontal stress direction, Mpa; μ is the poisson's ratio which is a function of the pore pressure depletion and is determined after rock mechanics experiments, dimensionless; ω_1 and ω_2 are respectively the tectonic stress coefficients used to express the contribution of the tectonic geological forces in the direction of the maximum and minimum horizontal stress direction, dimensionless; σ_v is the vertical stress, MPa, α is the Biot's coefficient, dimensionless, Pp is the pore pressure, Mpa; $P_{f(initial)}$ and $P_{f(depletion)}$ are respectively the initial pore pressure and the pore pressure after reservoir depletion, MPa.

2.3. Safe mud window

The mud window specifies the mud weight range for which the wellbore can be safely drilled without risk of instabilities. The lower and upper values of the mud window are obtained using respectively the shear and tensile failure conditions. The shear failure is expressed using the following Mohr-Coulomb failure criterion:

$$(\sigma_1 - \alpha P_p) \geq (\sigma_3 - \alpha P_p)tan^2(\frac{\pi}{4} + \frac{\emptyset}{2}) + \sigma_c \quad (3)$$

The failure in tensile mode appears when the following condition is fulfilled:

$$(\sigma_1 - \alpha P_p) \leq -|\sigma_t| \quad (4)$$

where, σ_c and σ_t are respectively the uniaxial compressive strength and the tensile strength of the rock that vary with the pore pressure depletion, MPa; $\emptyset$ is the internal friction angle; σ_3 and σ_1 are respectively the minimum and maximum principal stresses.

3. Presentation of data and results

3.1. Rock mechanics experiments results

This section investigates the impact of the reservoir depletion on the rock mechanical properties. The experimental results obtained for a confining pressure of 25 MPa at a depth of 1443.73 m are shown in table 1 for seven decreasing cases of pore pressure in simulating the reservoir depletion (1.06 g/cm^3; 0.96 g/cm^3; 0.86 g/cm^3; 0.76 g/cm^3; 0.66 g/cm^3; 0.56 g/cm^3; 0.46 g/cm^3). The variation law of Young's modulus, compressive strength, poisson's ratio and tensile strength are respectively plotted in Figs. 5.a, b, c and d.

Table 1. Experimental results of rock mechanical parameters under different pore pressure conditions
(Confining pressure = 25MPa, Depth =1443.73 m)

Number	Length（mm）	Diameter（mm）	Pore pressure(g/cm^3)	Compressive strength（MPa）	Tensile strength（MPa）	Elastic modulus（GPa）	Poison's ration
1	49.74	25.22	1.06	62.62	1.32	3.95	0.28
2	48.86	25.22	0.96	64.3	1.37	4.56	0.27
3	49.82	25.24	0.86	67.36	1.43	4.93	0.26
4	50.53	25.24	0.76	69.40	1.471	5.72	0.26
5	48.96	25.22	0.66	71.36	1.51	6.64	0.25
6	49.64	25.24	0.56	73.51	1.56	7.23	0.25
7	49.67	25.26	0.46	74.38	1.58	8.42	0.24

The results demonstrated that the compressive strength, the tensile strength and the elastic modulus increased with the decrease of pore pressure under constant confining pressure, whereas the Poisson's ratio decreased with the pore pressure. In fact, when the confining pressure is applied on the rock, the pores of the rock will be forced to reduce and the fractures will be closed, and the rock particles will tend to approach each other. In addition, as the effective stress on the matrix (the confining pressure minus the pore pressure) increases due to the pore pressure decrease, the contact stress between the rock particles will increase, the compressive strength and tensile strength of the rock will increase and the corresponding elastic modulus will also increase and the rock is less likely to be damaged by external forces. At the same time, as the pressure of the pore reduces, the force contributed by the pore pressure to the radial direction of the rock decreases, and the binding force of the rock in the radial deformation decreases, which will lead to a Poisson's ratio decrease.

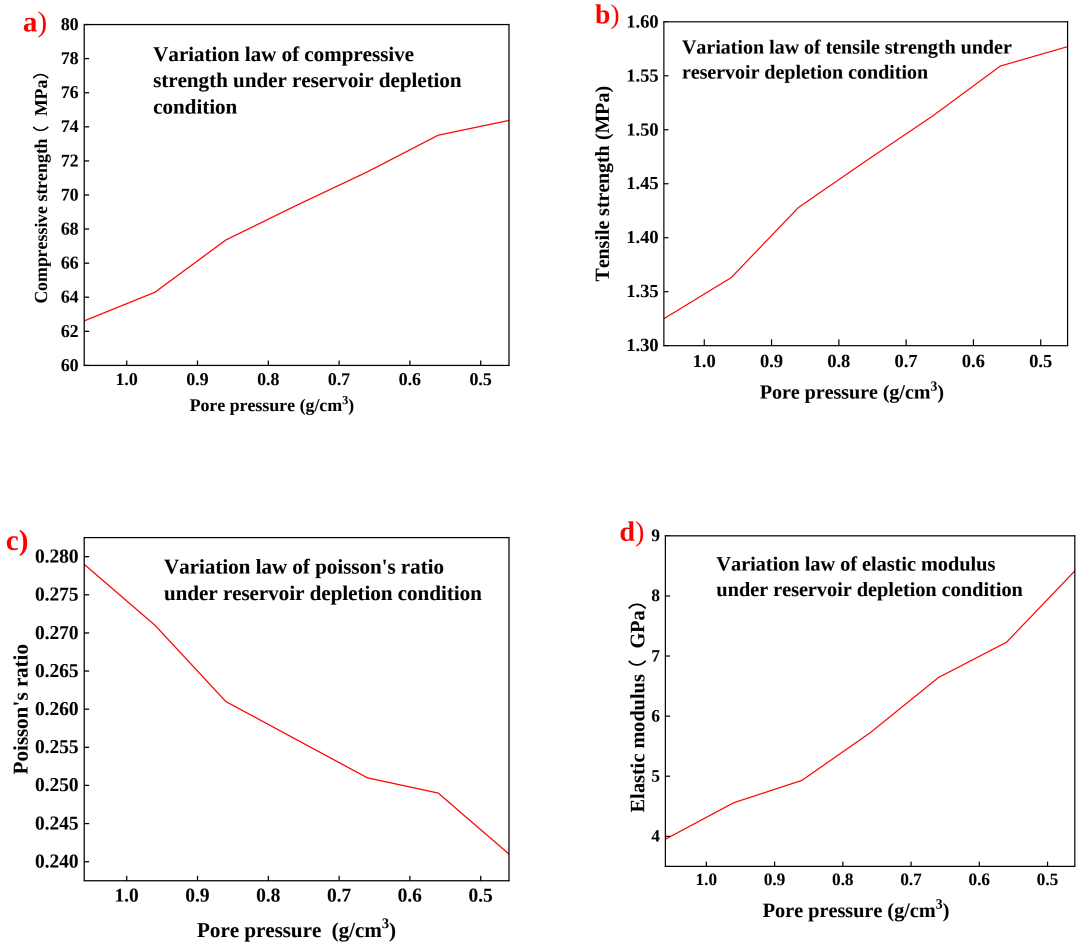

Fig. 5. Variation law of rock mechanical parameters under reservoir depletion condition. a) Compressive strength; b) Tensile strength; c) Poisson's ratio; d) Elastic modulus

3.2. Safe mud window

The mud window specifies the mud weight range for which the wellbore can be drilled safely without risk of instabilities. The lower and upper values of the mud window are obtained using respectively the shear and tensile failure conditions. The mud windows can be determined by combining fracture and collapse gradients results. Figs. 6-7 respectively show the mud windows in function of the wellbore inclination at the initial stage and after depletion in the maximum and minimum horizontal stress direction. The directions of minimum and maximum horizontal stresses are respectively 30° and 120° measured clockwise from the vertical axis. The azimuth angle ranges from 0° to 360° while the wellbore inclination angle varies from 0° to 90° in the radial direction.

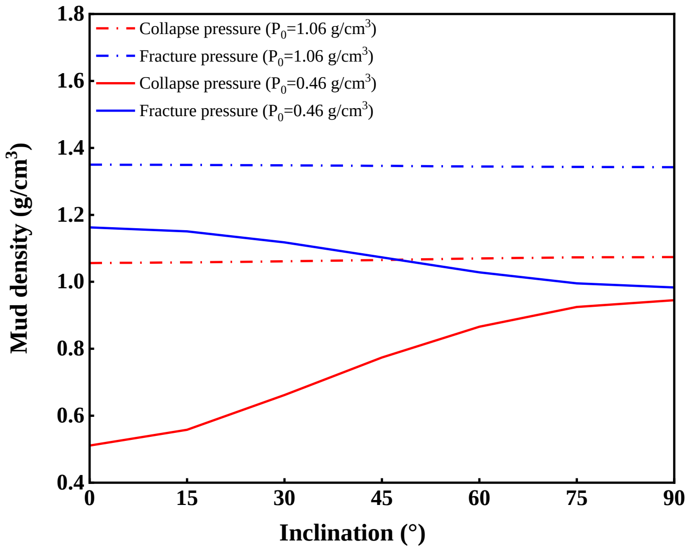

Fig. 6. Mud window in function of the wellbore inclination before depletion ($\boldsymbol{P_0 = 1.06}$ $\mathbf{g/cm^3}$) and at the final stage of depletion ($\boldsymbol{P_0 = 0.46}$ $\mathbf{g/cm^3}$) in the direction of the maximum horizontal stress.

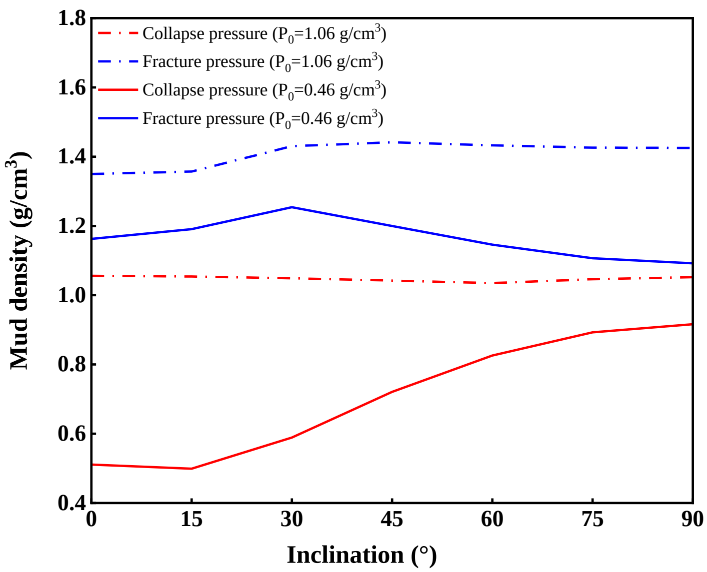

Fig. 7. Mud window in function of the wellbore inclination before depletion ($\boldsymbol{P_0 = 1.06\ g/cm^3}$) and at the final stage of depletion ($\boldsymbol{P_0 = 0.46\ g/cm^3}$) in the direction of the minimum horizontal stress

The results demonstrated that the fracture gradients globally declined with pore pressure depletion. In fact, the reservoir depletion is accompanied with a decrease in the total minimum horizontal stress σ_h and an increase in the effective minimum horizontal stress σ_h' and overburden stress σ_v' due to the Poisson effect related to $\frac{v}{1-v}$ which results in a reduction of the fracture pressure in the depleted zone. Similar researches in the literature have equally demonstrated that the fracture pressure linearly decreases with the reservoir pressure depletion in isotropic reservoirs (Dusseault, 2010; Zhao, Yuan, Feng and Yan, 2018). It is equally observed that the collapse gradient always decreased with the pore pressure depletion. In fact, under depleted reservoir conditions, the rock compressive strength increases and is less likely to be damaged by external forces; therefore in this situation, the wellbore will require less amount of mud weight to avoid wellbore collapse.

In general, the mud window in the direction of the maximum and minimum horizontal stress will narrow with the pore pressure depletion especially for high inclination angles because in that direction the fracture gradient decreases fastly and the collapse gradient increases rapidly. In fact, for the inclination angle of 90° the initial mud window (pore pressure=1.06$\mathrm{g/cm^3}$) in the direction of the minimum horizontal stress reduced by 52.80% after reservoir depletion (pore pressure =0.46$\mathrm{g/cm^3}$) while it reduced by 85.78% in the maximal horizontal stress direction. The deviated wellbore drilled along the maximum horizontal stress direction is highly prone to wellbore instability (the gap between fracture gradient and collapse gradient for the horizontal wellbore drilled in that direction is $0.038\ \mathrm{g/cm^3}$) due to its extremely narrow mud window while the horizontal well drilled in the minimum horizontal stress direction, on the other hand, requires the least amount of mud to ensure wellbore stability, therefore for the purpose of wellbore stability it is highly recommended to drill in the direction of the minimum horizontal stress.

4. Conclusion

This paper has analyzed the influence of the rock mechanical parameters on the wellbore stability under depleted reservoir conditions. The effect of pore pressure depletion on the rock mechanical parameters was first of all investigated by conducting experiment tests. Then, Python programming was developed to determine the stress distribution around the wellbore and the safe mud window under different depleted reservoir conditions. The main conclusions showed that:

1) The compressive strength, the tensile strength and the elastic modulus increased under depleted reservoirs condition whereas the poisson's ratio decreased with the pore pressure reduction;
2) The fracture and collapse gradients globally declined under depleted reservoir condition;
3) The mud window narrowed with the pore pressure reduction, for the inclination angle of 90° for example, the initial mud window in the direction of the minimum horizontal stress reduced by 52.80% after reservoir depletion while it reduced by 85.78% in the direction of the maximal horizontal stress.

The results obtained in this research can provide guidance during drilling in mature oilfields because it can enable to determine the percentage of the reduction of the safe mud window after reservoir depletion which is important to accurately design the mud window during drilling operations.

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