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Original article

The influence of water-based drilling fluid on mechanical property of shale and the wellbore stability

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A B S T R A C T

Because of high cost and pollution of oil-based drilling fluid, the water-based drilling fluid is increasingly used now. However, bedding planes and micro-cracks are rich in shale formation. When water-based drilling fluid contacts formation rock, it causes the propagation of crack and invasion of drilling fluid, which decrease shale strength and cause wellbore instability. In this paper, we analyzed influence of water-based drilling fluid on shale strength and failure mode by mechanics experiment. Based on those experimental results, considering the effect of bedding plane and drilling time, we established modeling of wellbore stability for shale formation. The result from this model indicates that in certain azimuth of horizontal well, collapsing pressure increases dramatically due to shale failure along with bedding plane. In drilling operation, those azimuths are supposed to be avoided. This model is applicable for predication of collapsing pressure in shale formation and offers reference for choosing suitable mud weight.

1. Introduction

As a kind of unconventional energy sources, currently shale gas plays an important role in industrialization exploration of the natural gas [1]. In the shale gas exploration and development, the United States is leader in the world. Though China has abundant shale reserves as America, the development of shale gas is on elementary stage and faces so many challenges. Especially in drilling operation, borehole collapse has been a common problem [2], which increases drilling period and cost.

In view of the instability problem, normally oil-base drilling fluid is the first choice because of its relatively strong plugging and inhibitive property. But the defect of oil-base drilling fluid is too expensive and harmful to environment [3]. On the contrary, water-based drilling fluid has comparatively low prize and pollution. Therefore, many scholars are trying to develop an efficient water-based drilling fluid for shale formation. However, shale formation has strong anisotropy and sensitive for water fluid, leading to serious instability problems in drilling process.

In this paper, composition and structure of shale have been investigated by means of X-ray diffraction (XRD) and Scanning electron microscope. Meanwhile, triaxial compression test and shear test have been applied to observe its mechanics property. By those experiments, the effect of water-based drilling fluid on structure and mechanics can be analyzed. Those analyses indicate that crack propagation and bedding plane are two key factors of causing borehole collapse in shale formation. According to the result, we establish a wellbore stability model for shale formation. This model is practical for analyzing wellbore stability in shale formation.

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2. Structure and composition of shale

2.1. Structure of shale

Rock samples were taken from Southern China Longmaxi formation of black shale. Bedding plane is clearly observed from

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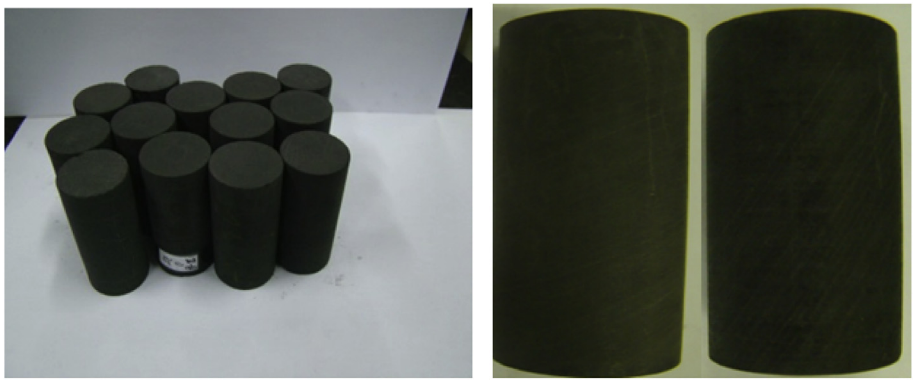


Fig. 1. Shale core samples.

standard shale cores (Fig. 1). Moreover, Scanning electron microscope was applied to observe substructure morphology of shale. The result in Fig. 2 shows micro-cracks and micro-pores are rich inside shale. By measurement, width of micro-cracks ranges from 0.4 μm to 3 μm.

2.2. Mineral composition and content analysis

XRD analysis results are presented in Table 1 and Table 2. In those samples, brittle mineral (quartz, plagioclase and calcite) is predominated and its average content is 80.77%, whereas clay mineral only averages 12.92% and ranges between 11.12% and 14.10%. In clay mineral, illite is the main content and averages 85.80%. Montmorillonite is extremely little and only averages 0.01%.

It is noted that content of brittle mineral is very high and clay mineral is not the abundant one in the component. In addition, Montmorillonite and illite smectite, which have strong hydration and swelling property, are in low content. According to that, the shale from Southern China Longmaxi formation is typical brittle shale and has weak hydration. So hydration swelling is not the key factor for borehole collapse.

3. Effect of water-based drilling fluid on mechanics of shale

Bedding plane has huge impact on strength of shale [4,5]. To analyze this type of mechanics structure, we assume that shale rock is composed by 2 parts—rock matrix and bedding plane. We use 2 methods to get shale strength by shear test (Fig. 3) so that obtain the strength of rock matrix and bedding plane respectively. In this experiment, we can get strength of rock matrix by shearing core in the direction perpendicular to bedding plane (Fig. 3a) and strength of bedding plane by shearing core in the direction parallel to the bedding plane (Fig. 3b).

According to above methods, shear test was used to obtain the strength of matrix and bedding plane after shale was soaked with water-based drilling fluid in different time. The results are presented in Fig. 4 and 5.

From results of Figs. 4 and 5, internal friction angle and cohesion of rock matrix are higher than bedding plane, which indicates bedding plane is relatively weak plane. After soaking water-based drilling fluid, the strength of bedding plane declines more quickly, which means that bedding plane is affected more by drilling fluid. The reason for that is the bedding plane has relatively high permeability, compared to rock matrix [6]. Therefore, it is easier for drilling fluid to penetrate inside. Consequently, bedding plane is more sensitive to water-based drilling fluid. Compared with decline trend of rock matrix and bedding plane, it is similar. Both of they drop dramatically firstly and then become stable in the late stage, which means the influence of drilling fluid is more obvious in initial stage.

To analyze the failure mode of shale, triaxial test was conducted along with the parallel and perpendicular direction of bedding plane, as shown in Fig. 6. Broken shale cores after triaxial test are illustrated in Figs. 7 and 8. Based on the results, different compressing direction has little influence on failure mode, which is still mainly single shear failure mode. In addition, there are several cracks around shear plane. With increase of

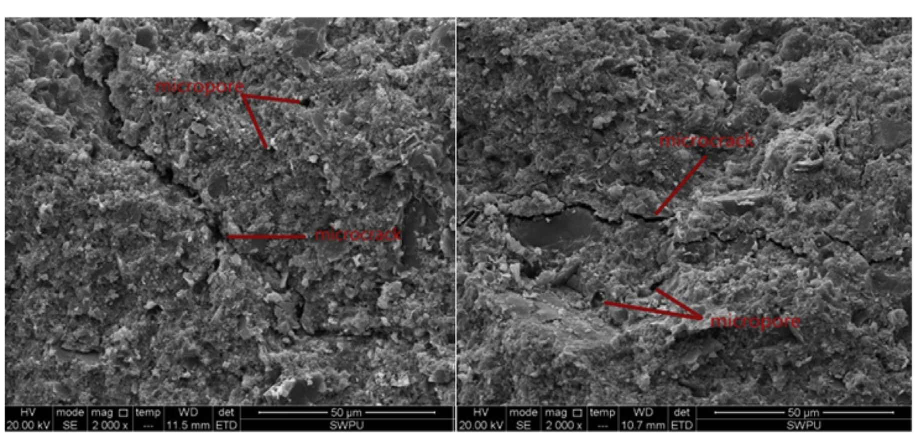


Fig. 2. Substructure morphology shale specimens.

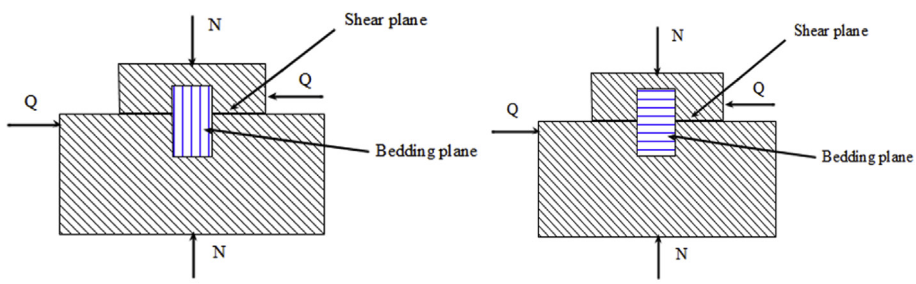
Table 1
Mineral composition and content.

Sample	Mineral composition (%)					
	Clay mineral	Pyrite	Quartz	Plagioclase	Calcite	Dolomite
1	14.10	2.51	57.87	3.82	17.50	4.20
2	11.12	1.80	61.41	2.11	20.01	3.55
3	13.68	1.91	58.75	2.01	17.92	5.73
4	12.76	2.13	60.01	2.92	18.73	3.45

Table 2
Clay minerals relative content.

Sample	Clay mineral content (%)				
	Illite	Montmorillonite	Illite smectite	Kaolinite	Chlorite
1	86.39	0.02	6.02	0.02	6.56
2	88.89	0.01	7.48	0.01	4.01
3	82.76	0.02	10.40	0.01	5.82
4	85.19	0.01	9.35	0.02	5.43

soaking time, the failure mode is still same but more cracks occur. Parts of those cracks are connected with each other, forming a crack network zone. The reason of the phenomenon is that drilling fluid invades into shale after soaking, which leads to crack propagation and strength decrease. So for brittle shale with low hydration, the key point for drilling fluid is its sealing capacity to prevent invasion.



(a) Rock matrix (b) Bedding plane

Fig. 3. Schematic of shear test for obtaining strength of rock matrix and bedding plane.

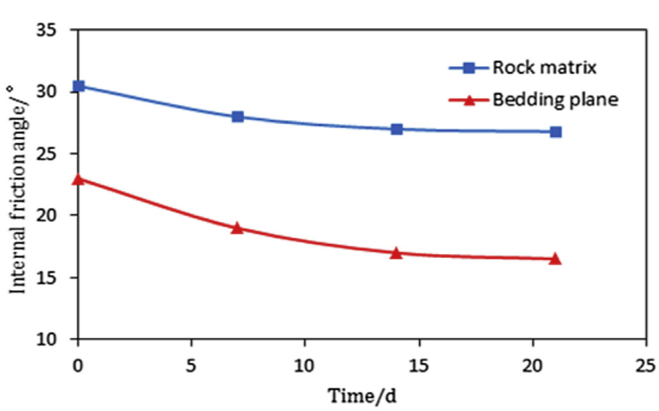


Fig. 4. Curve of friction angle of shale bedding plane and matrix in different soaking time.

4. Wellbore stability modeling

At present, for shale formation exploration and development, in order to obtain greater production, the horizontal well is the first option. But horizontal well has long drilling time. In the late stage of drilling, the instability problems are getting worse. So this model takes horizontal well as case.

Based on the linear elastic mechanics, the single weak-plane strength theory and Mohr-Coulomb criterion, effective stress around the borehole was obtained by coordinate conversion [7] (Fig. 9). The coordinate conversion equations are shown as follows:

$$\begin{cases} \sigma_r = p_i - \delta\phi\left(p_i - p_p\right) \\ \sigma_\theta = \sigma_{xx} + \sigma_{yy} - 2\left(\sigma_{xx} - \sigma_{yy}\right)\cos 2\theta - 4\sigma_{xy}\sin 2\theta + K_1\left(p_i - p_p\right) - p_i \\ \sigma_z = \sigma_{zz} - 2v\left[\left(\sigma_{xx} - \sigma_{yy}\right)\cos 2\theta + 2\sigma_{xy}\sin 2\theta\right] + K_1\left(p_i - p_p\right) \\ \tau_{\theta z} = 2\left(\sigma_{yz}\cos\theta - \sigma_{xz}\sin\theta\right) \\ \tau_{r\theta} = \tau_{rz} = 0 \end{cases} \tag{1}$$

$$\begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \alpha_{zz} \end{bmatrix} = [L]\begin{bmatrix} \sigma_H & & \\ & \sigma_h & \\ & & \sigma_v \end{bmatrix}[L]^T \tag{2}$$

$$L = \begin{bmatrix} \cos\beta\cos\alpha & \cos\beta\sin\alpha & -\sin\beta \\ -\sin\alpha & \cos\alpha & 0 \\ \sin\beta\cos\alpha & \sin\beta\sin\alpha & \cos\beta \end{bmatrix} \tag{3}$$

$$K_1 = \delta\left[\frac{\zeta(1-2\nu)}{1-\nu} - \phi\right] \tag{4}$$

where σ_H, σ_h, σ_v are in-situ stress, MPa. σ_{xx}, σ_{yy}, α_{zz}, σ_{xy}, σ_{xz}, σ_{yz} are the stress components of the local wellbore coordinates, MPa. σ_r, σ_θ, σ_z are the radial stress, hoop stress and axial stress, MPa. $\tau_{\theta z}$, $\tau_{r\theta}$, τ_{rz} are three components of the shear stress, MPa. v is Poisson's ratio. ϕ is porosity, %.p_i is mud weight, MPa. p_p is pore pressure, MPa. δ is wellbore permeability coefficient. ζ is Biot coefficient. β is deviation angle, degree. α is well azimuth, degree.

As weak plane, the bedding plan has great effect on rock mechanics. Especially, the different dip and dip azimuth can make different situation for wellbore stability in shale formation. Therefore, as shown in Fig. 10, we use coordinate conversion to get state of stress on bedding plane from stress around borehole [8]. The equations can be written as follows:

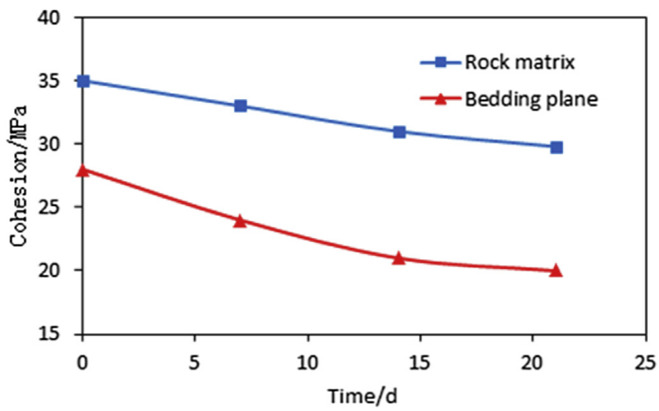


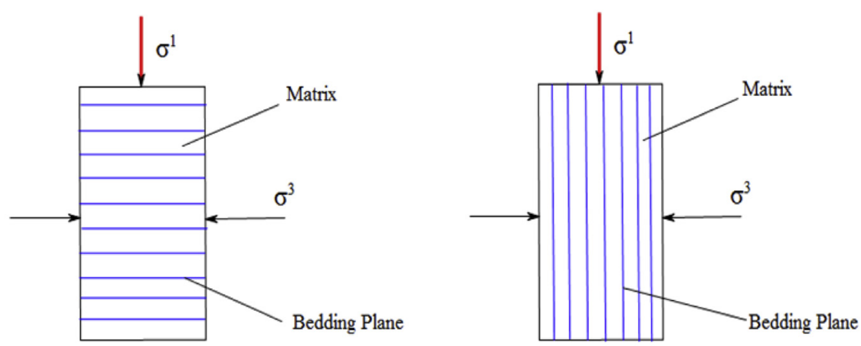
Fig. 5. Curve of cohesion of shale bedding plane and matrix in different soaking time.

$$\begin{bmatrix} \sigma^r_{xx} & \tau^r_{xy} & \tau^r_{xz} \\ \tau^r_{xy} & \sigma^r_{yy} & \tau^r_{yz} \\ \tau^r_{xz} & \tau^r_{yz} & \sigma^r_{zz} \end{bmatrix} = [R] \begin{bmatrix} \sigma_r & \tau_{r\theta} & \tau_{rz} \\ \tau_{r\theta} & \sigma_\theta & \tau_{\theta z} \\ \tau_{rz} & \tau_{\theta z} & \sigma_z \end{bmatrix} [R]^T \quad (5)$$

$$R = \begin{bmatrix} \cos(\beta_1-\beta)\cos(\alpha_1-\alpha) & \cos(\beta_1-\beta)\sin(\alpha_1-\alpha) & -\sin(\beta_1-\beta) \\ -\sin(\alpha_1-\alpha) & \cos(\alpha_1-\alpha) & 0 \\ \sin(\beta_1-\beta)\cos(\alpha_1-\alpha) & \sin(\beta_1-\beta)\sin(\alpha_1-\alpha) & \cos(\beta_1-\beta) \end{bmatrix} \quad (6)$$

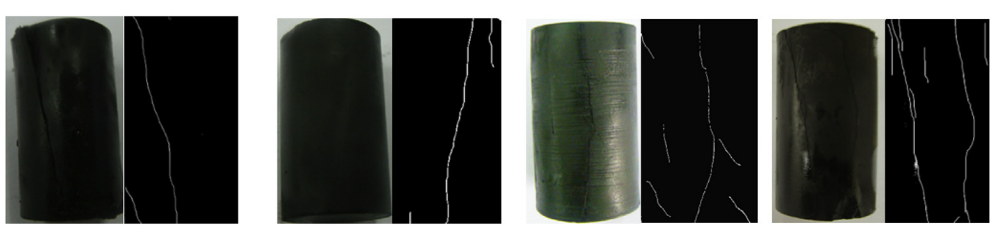
where β_1 is dip angle of bedding plane, degree. α_1 is dip azimuth angle of bedding plane, degree. σ^r_{xx}, σ^r_{yy} , σ^r_{zz} are normal stress on bedding plane, MPa. τ^r_{xy} , τ^r_{xz}, τ^r_{yz} are shear stress on bedding plane, MPa.

From coordinate conversion above, stress distribution around borehole and on bedding plane can be obtained. Based on the



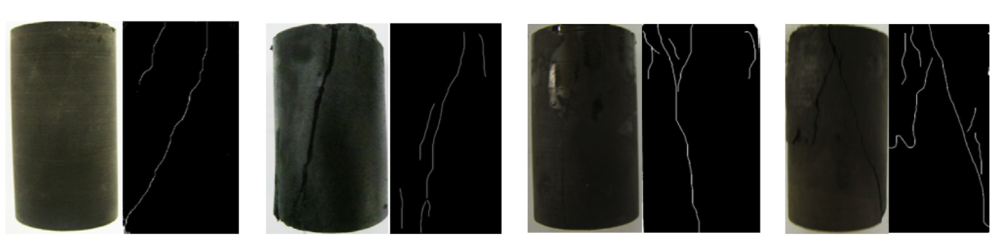
(a) Compressing in perpendicular direction (b) Compressing in parallel direction

Fig. 6. Schematic of 2 methods of triaxial compression test.



(a)Dry core sample (b) Soaking 7 days (c) Soaking 14 days (d) Soaking 21 days

Fig. 7. Broken shale core samples by compressing perpendicular direction in different soaking time.



(a)Dry core sample (b) Soaking 7 days (c) Soaking 14 days (d) Soaking 21 days

Fig. 8. Broken shale core samples by compressing parallel direction in different soaking time.

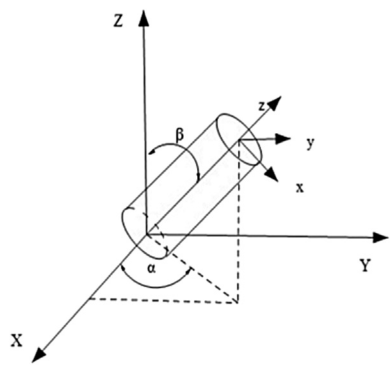


Fig. 9. Borehole coordinate system.

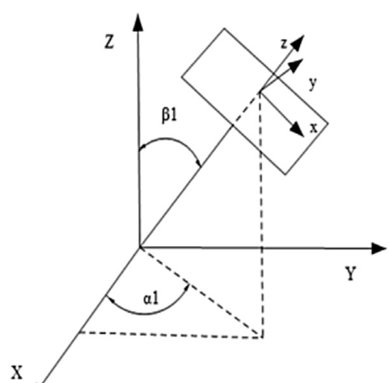


Fig. 10. Bedding plane coordinate system.

stress state, Mohr-Coulomb criterion is applied to determine shale failure along with rock matrix or bedding plane.

If shale rock failure is along with the bedding plane, according to Mohr-Coulomb criterion, the equation of failure criterion is shown as followed:

$$\begin{cases} \tau_r = C_w + \sigma_{nr} \tan(\varphi_w) \\ \sigma_{nr} = \sigma_{xx}^r \\ \tau_r = \sqrt{\left(\tau_{xy}^r\right)^2 + \left(\tau_{xz}^r\right)^2} \end{cases} \tag{7}$$

If shale rock failure is on the matrix, the equation of failure criterion can be expressed by the following equation:

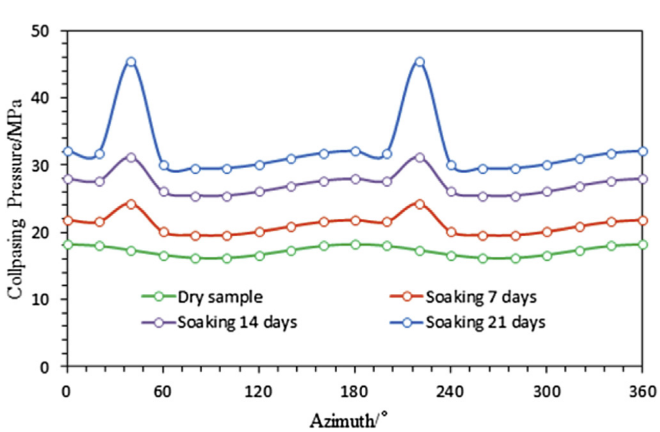


Fig. 11. Collapse pressure with 0° dip in different azimuth and soaking time.

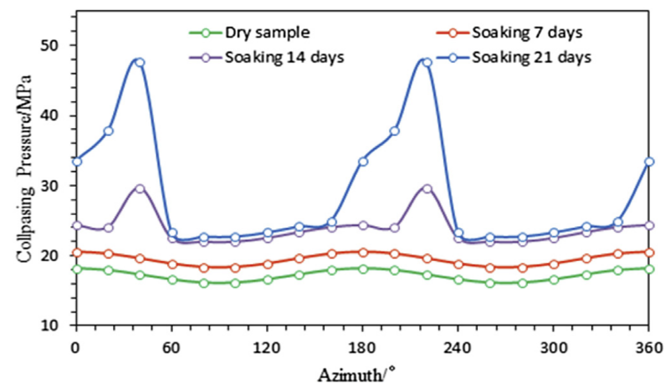


Fig. 12. Collapse pressure with 30° dip in different azimuth and soaking time.

$$\begin{cases} \sigma_1 = \sigma_3 \tan^2\left(45 - \frac{\varphi}{2}\right) + 2C\cot\left(45 - \frac{\varphi}{2}\right) \\ \sigma_1 = \frac{\sigma_z - \sigma_\theta}{2} + \sqrt{\left(\frac{\sigma_\theta - \sigma_z}{2}\right)^2 + \sigma_{\theta z}^2} \\ \sigma_3 = p_i - \delta\phi\left(p_i - p_p\right) \end{cases} \tag{8}$$

where C_w is cohesion of bedding plane, MPa. C is cohesion of rock matrix, MPa. φ_w is internal friction angle of bedding plane, degree. φ is internal friction angle of rock matrix, degree. σ_1, σ_3 is the maximum principal stress and minimum principal stress respectively, MPa.

Based on above equations, if we want wellbore not collapsed, the minimum drilling fluid pressure is supposed to keep shale stable in both matrix and bedding plane. So the collapse pressure can be acquired by above equations.

5. Case analysis

A case study on Southern China Longmaxi formation with our model is in the following.

According to drilling date from oilfield, overburden pressure is 68 MPa, maximum horizontal principal stress is 62 MPa and minimum horizontal principal stress is 49 MPa. Pore pressure is 30 MPa. Porosity is 7.4%. Rock mechanical parameters are taken from previous experiments.

Using the above datum into model, with the same azimuth angle of bedding plane (10°) and the same well azimuth angle

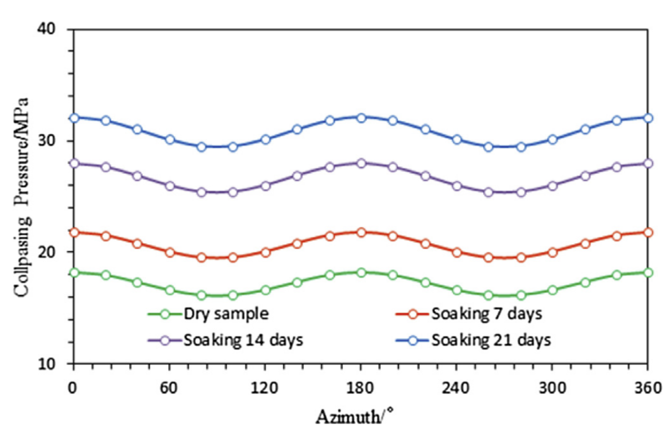


Fig. 13. Collapse pressure with 60° dip in different azimuth and soaking time.

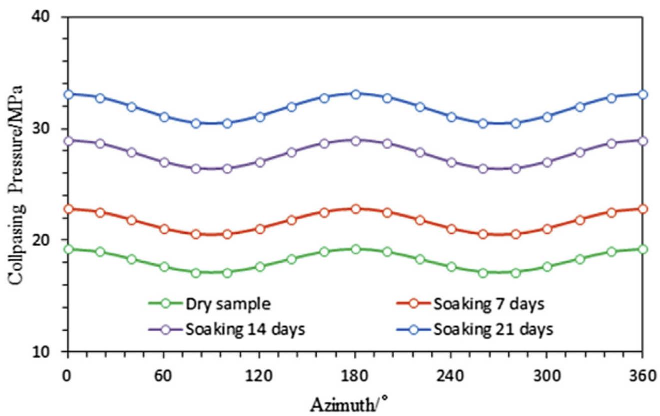


Fig. 14. Collapse pressure with 90°dip in different azimuth and soaking time.

(90°), we plot collapse pressure distribution with different borehole azimuth angle and different dip of bedding plane. The results are illustrated in Figs. 11–14.

From Figs. 11–14, with the increase time of contacting water-based drilling fluid, collapse pressure grows. Besides, bedding plane only affects shale strength in low dip. When dip of bedding plane is between 0° and 30°, as shown in Figs. 11 and 12, shale is broken along with bedding plane in azimuth from 20° to 60° and from 200° to 240°. It is noted that, when shale failure along with bedding plane, the collapse pressure will grow dramatically. When dip is 60° and 90°, as shown in Figs. 13 and 14, shale formation is damaged in rock matrix and has relatively low collapse pressure compared to shale failure along with bedding plane.

High collapse pressure means it is easy to be collapsed in this area. Therefore, high mud density is necessary. However, too high mud density tends to cause leakage of formation. So during drilling operation, we should avoid the azimuth with high collapse pressure in order to ensure the safety of drilling. In this case, azimuth from 20° to 60° and from 200° to 240° need to be avoided in drilling.

6. Conclusion

After experiment and analyzing collapse pressure based on calculation results of model, we have conclusion in the following.

(1) The content of clay minerals in Longmaxi shale is very low and does not have strong hydration expansion. But micro-crack develops very well. Hence drilling fluid may intrude the rock along with crack, causing it propagation and resulting in borehole instability. So during drilling operation, when water-based drilling fluid is used, sealing ability is the first consideration.
(2) Based on mechanical experiment, strength of bedding plane is clearly lower than rock matrix. Meanwhile, after soaking drilling fluid, drop range of bedding plane is larger than rock matrix, which indicates bedding plane is more sensitive to fluid.
(3) Shale mechanical strength would decline after soaking in the drilling fluid. In addition, crack develops more and connects with each other. The reason for this is that drilling fluid penetrates shale rock and then micro-crack expands after contacting water-based drilling fluid, resulting in the increase of the number of the cracks and the decrease of strength.
(4) Wellbore stability model of shale formation is established by means of coordinate transformation. Based on the calculation of the model, with the increase of soaking time, the strength of rock declines, collapse pressure goes up and the impact of bedding plane is more obvious. When the dip of bedding is low (0 or 30°) and the azimuth angle of well is from 20° to 60°and from 200° to 240°, collapse pressure rises sharply because of shale failure along with bedding plane. Therefore, those azimuths need to be avoided during drilling operation.

Acknowledgments

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