**Practical value.** Determination of the structure of pore space and porosity types of carbonate rocks under different pressure conditions makes it possible to allocate the complicated reservoir rocks at large depths and to predict their exploitability.

**Keywords:** *longitudinal wave velocity, variable pressure conditions, carbonate rock, hollow space structure*

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# BOREHOLE STABILITY IN STRATIFIED SHALE

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# СТІЙКІСТЬ СВЕРДЛОВИН У ШАРУВАТИХ ГЛИНИСТИХ СЛАНЦЯХ

**Purpose.** Stratified shale formation is prone to collapse in drilling. A method of precise calculation of collapse pressure should be developed to avoid severe wellbore instability of stratified shale.

**Methodology.** Clay mineral components of stratified shale were measured by X-ray diffraction, and microstructures of stratified shale were observed by scanning electron microscope. Shale cores had been drilled under different dip angles and then immersed in drilling fluids. Strength, cohesion and internal friction angle of stratifications and rock mass (vertical to the stratifications) were measured over different immersion time. The method suitable for calculating stratified shale strength has been developed. Based on the strength calculation method and circumferential stress distribution equation, the collapse pressure of stratified shale has been calculated.

**Findings.** The stratified shale is mainly composed of illite and kaolinite; and stratifications are actually 500 nm–30μm wide microcracks (stratified shale of Weizhou formation, Beibuwan basin, South China Sea). Cohesion and internal friction angle of stratification decrease in exponential rule with immersion time, while that of the rock mass decrease in linear rule with immersion time. The rock strength decreases firstly and then increases with the dip angle (0–90°); and the lowest value occurs at the dip angle 50–60; and single weak plane criterion is suitable for calculation of the strength of stratified shale. Contrasted to the drilling fluid density and wellbore stability situation while drilling stratified shale formation, it can be obtained that the numerical results of collapse pressure are quite precise.

**Originality.** Stratifications are microcracks developed in shale, and free water could seep inward shale through stratifications under capillary force. The method of calculating collapse pressure of stratified shale taking into account the seepage effect has been developed.

**Practical value.** The research results allow us to calculate precisely the collapse pressure of stratified shale under different deviation angles and azimuth angles. This contributes to optimization of drilling fluids density, wellbore trajectory and configuration while drilling in stratified shale.

**Keywords**: *shale, stratification, dip angle, hydration, single weak plane criterion, wellbore stability*

**Introduction.** Wellbore instability is a complex problem that commonly encountered in drilling engineering; and in 70% of cases the problem occurres in shale formation. With the surge of shale gas development, the growing number of deviate wells and horizontal wells make wellbore instability even more severe. The samples for shale hydration researches at present are mostly shale outcrop, their strength is closely related to the water content due to high content of smectite. Based on smectite hydration, relationships were established between shale strength and the factors such as water content [1], activity [2], efficiency of semi-permeable membranes [3], solute diffusion coefficient [4]. HTHP (High Temperature and High Pressure) can dehydrate smectite to illite and kaolinite, in consequence, shale in deep formations mainly consists of non swelling clays like illite and kaolinite, water absorption of which is too low to establish an effective function of water content and shale strength. Drilling practice also indicates that deep shale formation were often with approximate parallel stratifications. To test deep stratified shale properties, experimental cores were fetched from deep shale formation and severe wellbore instability had occurred while drilling in the formation. Hydrability and strength of these cores were tested, analytical model about stability of stratified shale was created and its applicability was validated. The calculated values were used to analyze the wellbore instability and countermeasures were applied.

**Materials and Methods. Core description.** The cores used in the experiments were from deep stratified shale of Weizhou formation at the Paleogene, Beibuwan Basin, South China Sea, which were wax-sealed before.

Cores for compressive strength test: diameter and length are 50mm and 25mm respectively. Setting up the angle between the axial direction of the core and normal direction of bedding plane for $\alpha$ , and cores were drilling with limiting $\alpha$ to 0°, 15°, 30°, 45°, 60°, 75°, 90°, respectively(as shown in Fig. 1).

Cores for shear strength test: Make cubic cores with different bedding angles in the above way. The edge length is 5 cm; each face is perpendicular to the adjacent one (maximum of the deviation should be less than 0.25°), and parallel to the opposite one(maximum of the non-parallelism should be less than 0,005 cm).

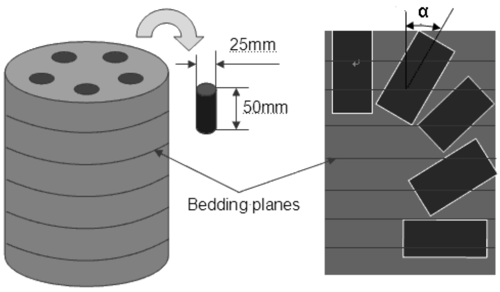



*Fig. 1. The method of cores drilling with different stratification dip angles*

**Experimental method.** Immersed the cores in PEM drilling fluid used in drilling Weizhou shale formation (additives as shown in Table 1), stirred the drilling fluid to keep fluid flowing while immersing, and water absorption amount of cores are measured after experiment ended. Afterwards, the uniaxial compressive strength and the shear strength were tested.

*Table 1*

Additives of PEM drilling fluid

| Additives | Dosage kg/m³ | Additives | Dosage kg/m³ |
|---|---|---|---|
| NaOH | 2.0 | $NaCO_3$ | 2.0 |
| Bentonite | 30 | PAC-LV | 4.0 |
| PLUS | 7.5 | XC-H | 2.0 |
| TEMP | 15 | KCl | 40 |
| SMP-1 | 15 | LSF | 15 |
| LPF | 15 | DYFT-2 | 15 |
| JLX-C | 40 | GRA | 15 |

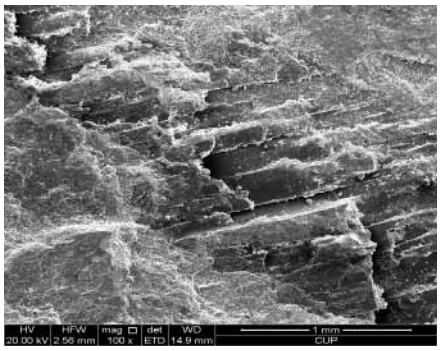
**Experimental results and discussions.** XRD (X-ray diffraction) was utilized to analyze compositions of clay minerals of 6 shale cores of Weizhou formation; the results are shown in Table 2. Shale of Weizhou formation mainly consists of illite and kaolinite, both of which occupy 70–85%. Strong interlaminar stress of the illite and kaolinite could avoid water molecules from invading lamellae, so they soak up less water and revealed low hydration, mass increments of the cores after immersion are all less than 5%.

SEM (scanning electron microscope) magnified shale of Weizhou formation 100 times (Fig. 2, *a*) and 10,000 times (Fig. 2, *b*) to observe stratification microstructure. The parallel stratification is developed and the stratification spacing is 1–3 μm, more SEM observations demonstrate that the stratification spacing of shale in Weizhou formation is 500 nm–30 μm. The micro-gaps are natural capillaries, and shale is hydrophilic mineral, free water permeate inward shale along the micro-gaps under capillary force. Fig. 3 shows the shale of the Weizhou formation, which is dried on surface after soaking in the distilled water for 5 hours. There are large amounts of water among the micro-gaps, and water invasion could increase the stratification spacing and even lead to shale failure. Meanwhile, the water adoption of the continuous structure of rock mass is low.

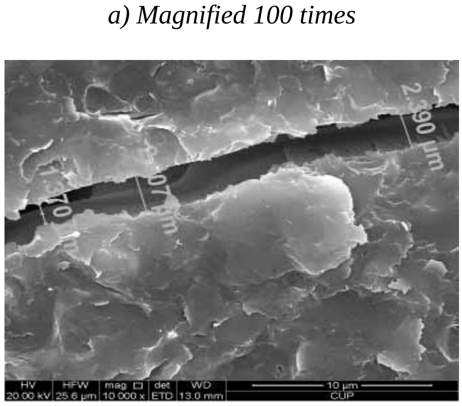
*Table 2*

Components analysis of clay minerals in stratified shale of Weizhou formation

| Well depth /m | Smectite /% | Illite /% | Kaolinite /% | Chlorite /% | Illite/ smectite formation | |
|---|---|---|---|---|---|---|
| | | | | | Illite /% | Smectite /% |
| 2362,5 | 0 | 21.2 | 44.9 | 17.6 | 10.7 | 5.6 |
| 2338,7 | 0 | 15.7 | 50.1 | 17.4 | 8.9 | 7.9 |
| 2391,7 | 0 | 22.6 | 44.6 | 17.2 | 6.3 | 9.3 |
| 2396 | 0 | 13.2 | 60.1 | 13.2 | 9.7 | 3.8 |
| 2484,8 | 0 | 39.1 | 41.8 | 11.6 | 2.3 | 5.2 |
| 2486 | 0 | 13.2 | 43.2 | 20.5 | 19.2 | 3.9 |



*a) Magnified 100 times*



*b) Magnified 10,000 times*

*Fig. 2. SEM photos of the stratified shale microstructure*

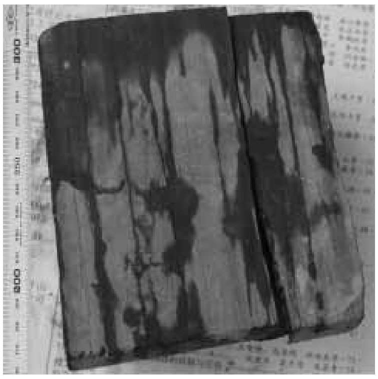


*Fig. 3. Surface dried shale after immersing in distilled water for 5 hours*

Cohesion and internal friction angle are two critical strength parameters, but there is no uniform understanding of their physical meanings. Changbing Chen [5] presents that cohesion are mainly cementation stress. Mohr-Coulomb Criterion [6] expresses that internal friction angle can be related to friction resistance coefficient of failure surface. The adsorbed water decreases the cementation strength by reacting with the cement. Chunhe Yang [7] considered that the cementation strength of illite (as stratifications cement) is decreased by interacting with water (equation 1).

$$K_{0.9}Al_{2.9}Si_{3.1}O_{10}(OH)_2 + nH_2O \rightarrow K_{0.9}Al_{2.9}Si_{3.1}O_{10}(OH)_2\, nH_2O. \quad (1)$$

Xiaojia Zhu [8] considered that reaction between illite and water can lead to 0.7%–1.5% expansion and 0.03–0.1 MPa swelling force generated in the vertical direction among the stratifications. The longer the soak time is, the deeper the water invades, and the larger the cohesion decreases. Acting as lubricant, water may decrease friction resistance between the stratifications. Shear strength testes have been done along the direction parallel to the stratification plane and perpendicular to the bedding plane respectively. The cohesion and internal friction angle of stratification and rock mass of shale cores are determined by the shear strength test (Fig. 4). Cohesion and internal friction angle of the stratification decreased in exponential rule with immersion time, and that of the rock mass decreased in linear rule with immersion time, as show in regression equations 2.

$$\begin{cases} c_w = 5{,}1297e^{-0{,}0111t} \\ \eta_w = 24{,}267e^{-0{,}0053t} \\ c_r = -0{,}0167t + 7{,}7 \\ \eta_r = -0{,}0284t + 29{,}6 \end{cases}, \quad (2)$$

where $c_w$ is cohesion of stratification; $\eta_w$ is internal friction angle of stratification; $c_r$ is cohesion of rock mass; $\eta_r$ is internal friction angle of rock mass.

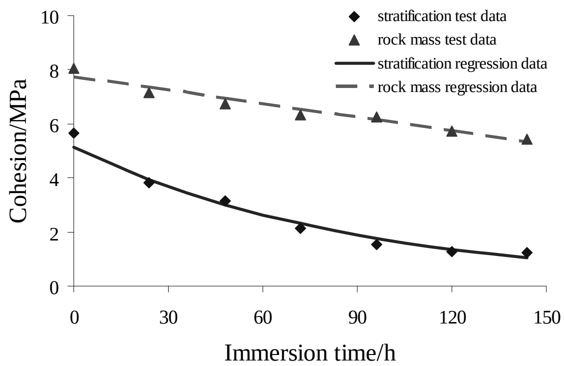
Shale strength decreases with the decrease of cohesion and internal friction angle. Fig. 4 shows the strength of cores with different stratification dip angles after immerging in drilling fluid. Setting up within the range of the dip angle $\beta_1 < \alpha < \beta_2$, the stratification would fail. The strength of the cores decreases with immersion time extension, and the decrease range of stratification are more than that of rock mass. Meanwhile, the dip angle range of stratification failure increases. The range is $40° < \alpha < 75°$ before immersion and is $22° < \alpha < 84°$ after immerging for 3 days. Compared to original strength, the strength after immersion of rock mass decreased by 6.4 MPa, while the strength of the stratification decreased by 21.7 MPa.

For rock with stratification structure, Jaeger [9] develops single weak plane criterion, as shown in equation (3) and equation (4).

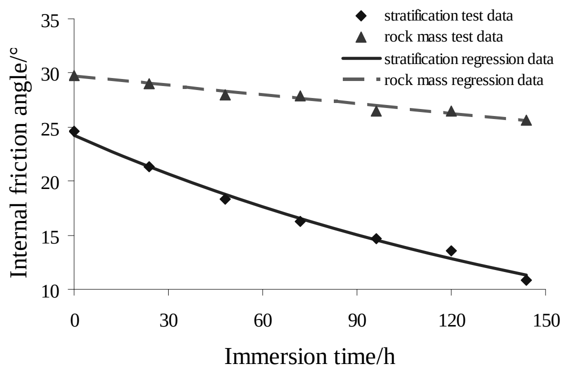
$$\sigma_{\max} - \sigma_{\min} = \frac{2(c_w + \sigma_{\min}\tan\eta_w)}{(1-\tan\eta_w\cot\alpha)\sin 2\alpha}; \quad (3)$$

$$\sigma_{\max} - \sigma_{\min} = 2(c_r + \sigma_{\min}\tan\eta_r)\left[\left(\tan^2\eta_r + 1\right)^{0.5} + \tan\eta_r\right], \quad (4)$$

where $\sigma_{\max} = \max(\sigma_1, \sigma_2, \sigma_r)$, $\sigma_{\min} = \min(\sigma_1, \sigma_2, \sigma_r)$, $\sigma_1$, $\sigma_2$, $\sigma_r$ are the three principal stresses on the failure surface.




*a)*




*b)*

*Fig. 4. Cohesion and internal friction angle of stratification and rock mass changing rule with immersion time: a) cohesion; b) internal friction angle*

Equation (3) is stratification failure equation, while the equation (4) is the rock mass failure equation. Equation (3) indicates that stratification failure only occurs when $\eta_w < \alpha < \pi / 2$, otherwise the rock mass will fail, which is consistent with the experimental results. Combined with equation (2), the theory can calculate the strength of stratified shale immerging different time. The experimental strength of stratified shale with different dip angels are show in Fig. 5 as point values, and theoretical strength by single weak plane criterion are also show in Fig. 5 as curve values. It can be seen that the criterion has high calculation accuracy.

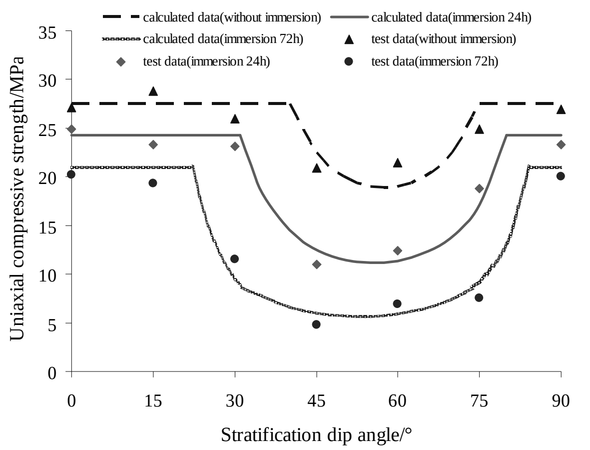



*Fig. 5. Experimental strength (point values) and theoretical strength (curve values) of cores with different stratification dip angles after immerging in drilling fluid*

**Establishment of wellbore stability model of deviated well.** Generally, the seepage of drilling fluids in shale formations can be ignored due to the low permeability of shale; while for stratified shale, since the micro-gaps are natural capillaries, seepage must be taken into consideration when determining circumferential stress. Combined with Darcy's law, circumferential stress distribution equation of deviated wells in polar coordinates is given in equation (5).

$$\begin{cases} \sigma_r = p_i - \phi(p_i - p_p) \\ \sigma_\theta = -p_i + \sigma_{xx}(1-2\cos 2\theta) + \sigma_{yy}(1+2\cos 2\theta) - 4\sigma_{xy}\sin 2\theta + \left[\frac{\alpha(1-2\mu)}{1-\mu} - \phi\right](p_i - p_p) \\ \sigma_z = \sigma_{zz} - \mu\left[2(\sigma_{xx} - \sigma_{yy})\cos 2\theta + 4\sigma_{xy}\sin 2\theta\right] + \left[\frac{\alpha(1-2\mu)}{1-\mu} - \phi\right](p_i - p_p) \\ \sigma_{\theta z} = -2\sigma_{xz}\sin\theta + 2\sigma_{yz}\cos\theta \\ \sigma_{r\theta} = \sigma_{rz} = 0 \end{cases} , \quad (5)$$

where $p_i$ is the mud density, $p_p$ is the equivalent density of the initial formation pressure, $\phi$ is the porosity, $\alpha$ is Biot coefficient, $\mu$ is passion ratio, $\theta$ is the angle between radius vector of a point on the wall and maximum in-situ stress direction.

Circumferential Stress distribution of deviated wells is shown in Fig. 6, equation (5) reveals that the failure surface of the wall is $\theta$-z plane. The normal stress and shear stress of the failure surface are shown in equation (6).

$$\begin{cases} \sigma = \sigma_\theta \cos^2\gamma + 2\sigma_{\theta z}\cos\gamma\sin\gamma + \sigma_z \sin^2\gamma \\ \tau = \frac{1}{2}(\sigma_z - \sigma_\theta)\sin 2\gamma + \sigma_{\theta z}\cos 2\gamma \end{cases} , \quad (6)$$

where $\gamma$ is the angle between the failure surface and $z$ axis.

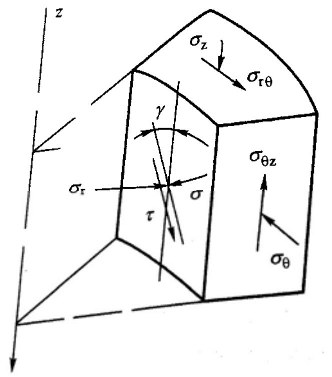



*Fig. 6. Circumferential stress distribution of deviated well*

$\sigma_r$ is principal stress on the failure surface, set $d\sigma / d\gamma = 0$, the other two angles of principal stresses can be calculated by equation 7.

$$\begin{cases} \gamma_1 = \frac{1}{2}\arctan\frac{2\sigma_{\theta z}}{\sigma_\theta - \sigma_z} \\ \gamma_2 = \frac{\pi}{2} + \frac{1}{2}\arctan\frac{2\sigma_{\theta z}}{\sigma_\theta - \sigma_z} \end{cases} . \quad (7)$$

Plug $\gamma_1$, $\gamma_2$ into equation (6), the other two principal stresses can be calculated by equation 8.

$$\begin{cases} \sigma_1 = \frac{\sigma_z + \sigma_\theta}{2} + \sqrt{\left(\frac{\sigma_z - \sigma_\theta}{2}\right)^2 + \sigma_{\theta z}^2} \\ \sigma_2 = \frac{\sigma_z + \sigma_\theta}{2} - \sqrt{\left(\frac{\sigma_z - \sigma_\theta}{2}\right)^2 + \sigma_{\theta z}^2} \end{cases} . \quad (8)$$

Plug three principal stresses on the failure surface $\sigma_r$, $\sigma_1$, $\sigma_2$ into single weak plane criterion. The collapse pressure of the stratification and rock mass can be obtained respectively.

**Field application.** For deviated wells with different orientations and different wellbore immersion time by PEM drilling fluid in Weizhou stratified shale formation, the caving pressures were calculated by single weak plane criterion, as shown in Fig. 7. Calculation parameters were as follows: well depth: $H$ =2053m, well size: $R_w$ =311.2mm, pore-pressure gradient:

$p_p$ =1.03g/cm$^3$, Biot coefficient: $\alpha$ =0.65, in-situ stress gradient: $\sigma_H$ =1.85g/cm$^3$, $\sigma_h$ =1.65g/cm$^3$, $\sigma_v$ =2.23g/cm$^3$, maximum horizontal in-situ stress orientation: $\omega$ =50°, minimum horizontal in-situ stress orientation: $\omega$ =140°, Poisson ratio: $\mu = 0,243$ .

The calculations results showed:

1. In the range of stratification failure deviation angles, the caving pressure increased rapidly, and the maximum value appeared when the deviation angle was between 55 and 65°.

2. With prolong of the immersion time, the strength of stratification decreased and the caving pressure increased rapidly. Along the maximum horizontal in-situ stress orientation, after 72 h immersion, the caving pressure enhanced about 0,49 g/cm$^3$ than the original state.

3. The range of stratification failure deviation angles enlarged with extension of immersion time.

4. The caving pressure along the maximum horizontal in-situ stress orientation was greater than that along the minimum horizontal in-situ stress orientation. The maximum different value was 0,18 g/cm$^3$ and increase with extension of immersion time.

5. In horizontal wells and vertical wells, rock mass will failure. The caving pressure of horizontal wells is 0.09–0.19 g/cm$^3$ greater than that of the vertical wells.

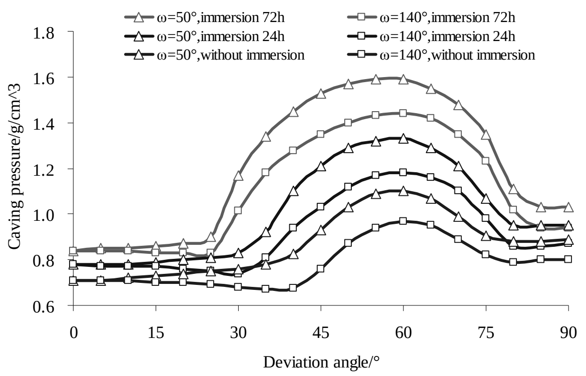



*Fig. 7. Caving pressures of Weizhou stratified shale formation calculated by single weak plane criterion*

The caving pressure is partly determined by the rock strength, deviation angle and azimuth angle. With prolong of the immersion time, the caving pressure will increase, and the caving deviation angle range of stratification failure will extend. Based on the above analysis, some measures to prevent wellbore instability of stratified shale can be concluded as follows:

1. Optimize borehole trajectory, reduce the deviation angle, and keep borehole azimuth along the minimum horizontal in-situ stress orientation.

2. Drill through the formation quickly and cement the stratified shale section as soon as possible.

Serious wellbore instability had occurred frequently when drilling stratified shale of Weizhou formation and the frequency reached up to 68,75% of all the wells in the area. Fig. 8 shows the schistose shale caving of Well X15. Table 3 shows wellbore stability situation of Weizhou formation of some wells after immersion for 72 h. The basis data of the wells are provided, such as deviation angle, azimuth angle, and theoretical caving pressure (Fig. 7), field drilling fluid density. Wellbore instability occurred when the drilling fluid density was lower than the theoretical value, otherwise, the wellbore kept stability. It can be seen that the circumferential stress distribution equation and single weak plane criterion are appropriate for the calculation of caving pressure of stratified shale in Weizhou formation.

To prevent stratified shale caving of Weizhou formation, the following measures were taken at a later stage in drilling process:

1. Reduce the deviation angle.

2. Keep drilling along with the minimum horizontal in-situ stress orientation.

3. Drill through the formation quickly by rotary steering drilling tool.

4. Before drilling stratified shale formation, increase the drilling fluid density to more than 1,50 g/cm$^3$. By adopting measures above, the serious wellbore instability of the stratified shale were solved ultimately.

*a)*

*b)*

*Fig. 8. Caving of stratified shale of Weizhou formation of Well X15: a) schistose shale cavings along the stratification plane; b) large amounts of schistose shale caving on the vibrating screen*

*Table 3*

Wellbore stability situation of stratified shale of Weizhou formation of the drilled wells

| Well No. | X1 | X2 | X3 | X8 | X15 | X18 |
|---|---|---|---|---|---|---|
| Deviation angle/° | 47.9 | 43.3 | 51.3 | 11.9 | 69.2 | 49.8 |
| Azimuth angle /° | 297.1 | 319.7 | 343.7 | 139.9 | 293.4 | 100.4 |
| Collapse pressure/g/cm^3 | 1.44 | 1.30 | 1.46 | 0.84 | 1.39 | 1.51 |
| Mud density/cm^3 | 1.42 | 1.56 | 1.58 | 1.36 | 1.30 | 1.45 |
| Wellbore stability situation | collapse | stable | stable | stable | serious collapse | collapse |

**Conclusion.** For shale in deep formation, the main clay minerals are illite and kaolinite, but stratification structures often exist. There are 500 nm–30 μm width microcracks among stratifications of shale in Weizhou formation. Free water can permeate inward shale along with the microcracks under capillary force.

As the lubrication of stratifications and softening of cements causing by water, cohesion and internal friction angle of stratifications decrease rapidly in exponential rule with immersion time. On the other hand, free water is difficult permeate into shale rock mass due to tis low permeability, and cohesion and internal friction angle of stratifications decrease slowly in linear rule with immersion time.

The strength of stratified shale is closely related to stratification dip angle. Stratification will slide and fail when the angle is high, and the failure strength is much lower than that of rock mass. Experiments demonstrated that the strength of shale with different stratification dip angles can be calculated accurately by single weak plane criterion. Under consideration of seepage effect, circumferential stress distribution equation is given. With different azimuth angles and deviation angles and immersion time, caving pressures of stratified shale in Weizhou formation are calculated.

The caving pressure of stratified shale is closely related to the deviation angle, azimuth angle and immersion time. With prolong of the immersion time, both the caving pressure and caving deviation angle range of the stratification increase. The caving pressure reached maximum value when the deviation angle was between 55° and 65°, and it gradually reduced from the maximum horizontal in-situ stress orientation to the minimum horizontal in-situ stress orientation. According to the research results, some measures were taken to solve the problem of wellbore instability of stratified shale in Weizhou formation, such as reducing the deviation angle, keeping borehole drilling along with the minimum horizontal in-situ stress orientation, increasing the mud density to more than 1,50 g/cm$^3$. The problem has been solved ultimately.

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**Мета.** При бурінні шаруватих формацій глинистих сланців часто відбувається руйнування свердловин. Аби уникнути руйнування свердловин у сланцях, необхідно розробити методи попереднього визначення критичного тиску у свердловині.

**Методика**. Мінеральний склад глинистих порід був досліджений за допомогою рентгенівської дифракції. Для вивчення мікроструктури глинистих порід був використаний електронно-скануючий мікроскоп. Зразки (керни) глинистої породи були вибурені під різними кутами, а потім занурені до бурового розчину. Міцність, зчеплення, кут внутрішнього тертя пластів і порідного масиву (перпендикулярно шаруватості) вимірювалися при різній тривалості занурення. На основі лабораторних даних відносно міцності кернів створена модель розрахунку міцності глинистих порід. З використанням розробленої моделі на основі рівнянь розподілу напруги в навколишньому масиві визначений критичний тиск, що призводить до руйнування свердловини.

**Результати**. Глинисті сланці, складені переважно іллітами й каолінітоми; шари мають мікротріщини завтовшки 500нм–30мкм (формації шаруватих глинистих сланців Вейджоу басейну Бейбуван у Південно-Китайському морі). Зчеплення та кут внутрішньо-

го тертя нашарувань зменшуються в експоненціальній залежності від часу занурення до розчину, тоді як порідного масиву – у лінійній. У міру зміни кута падіння від 0 до 90º міцність породи спочатку знижується, а потім зростає, досягаючи мінімальних значень при кутах 50–60º. Міцність шаруватих глинистих сланців визначається відповідно до критерію площини ослаблення. Отримане для даних умов значення критичного тиску, що призводить до руйнування свердловин у шаруватих глинистих сланцях, визначене практично достовірно.

**Наукова новизна**. Шаруватість – це мікротріщини всередині глинистих порід, через які вільна вода потрапляє до породи під дією капілярної сили. Розроблено метод розрахунку критичного тиску у свердловині, пробуреній у шаруватих глинистих сланцях, з урахуванням ефекту інфільтрації.

**Практична значимість.** Результати роботи дозволяють розраховувати критичний тиск у свердловині, пробуреній у шаруватих глинистих сланцях, при різних кутах падіння та азимутах. Це дозволяє оптимізувати щільність промивальної рідини, напрям буріння й конфігурацію свердловин.

**Ключові слова**: *сланець, шаруватість, кут нахилу, гідратація, критерій площини ослаблення, стійкість свердловини*

**Цель.** При бурении слоистых формаций глинистых сланцев часто происходит разрушение скважин. Чтобы избежать разрушения скважин в сланцах, необходимо разработать методы предварительного определения критического давления в скважине.

**Методика.** Минеральный состав глинистых пород был исследован с помощью рентгеновской дифракции. Для изучения микроструктуры глинистых пород был использован электронно-сканирующий микроскоп. Образцы (керны) глинистой породы были выбурены под разными углами и затем погружены в буровой раствор. Прочность, сцепление, угол внутреннего трения пластов и породного массива (перпендикулярно слоистости) измерялись при различной продолжительности погружения. На основе лабораторных данных в отношении прочности кернов создана модель расчёта прочности глинистых пород. С использованием разработанной модели на основе уравнений распределения напряжений в окружающем массиве определено критическое давление, которое приводит к разрушению скважины.

**Результаты. Г**линистые сланцы, сложены преимущественно иллитами и каолинитами; слои имеют микротрещины толщиной 500нм–30мкм (формации слоистых глинистых сланцев Вейджоу бассейна Бейбуван в Южно-Китайском море). Сцепление и угол внутреннего трения напластований уменьшаются в экспоненциальной зависимости от времени погружения в раствор, в то время как породного массива – в линейной. По мере изменения угла падения от 0 до 90º прочность породы сначала снижается, а затем возрастает, достигая минимальных значений при углах 50–60º. Прочность слоистых глинистых сланцев определяется в соответствии с критерием плоскости ослабления. Полученное для данных условий значение критического давления, приводящего к разрушению скважин в слоистых глинистых сланцах, определено практически достоверно.

**Научная новизна.** Слоистость представляет собой микротрещины внутри глинистых пород, через которые свободная вода попадает в породу под действием капиллярной силы. Разработан метод расчёта критического давления в скважине, пробуренной в слоистых глинистых сланцах, с учетом эффекта инфильтрации.

**Практическая значимость.** Результаты работы позволяют рассчитывать критическое давление в скважине, пробуренной в слоистых глинистых сланцах, при разных углах падения и азимутах. Это позволяет оптимизировать плотность промывочной жидкости, направление бурения и конфигурацию скважин.

**Ключевые слова:** *сланец, слоистость, угол наклона, гидратация, критерий плоскости ослабления, устойчивость скважины*

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