впливу наближення очисного вибою на напружено-деформований стан елементів системи кріплення демонтажного штреку.

**Практична значимість.** Отримані результати будуть використані при обґрунтуванні параметрів системи кріплення гірничих виробок у зоні впливу очисних робіт.

**Ключові слова:** *очисні роботи, демонтажний штрек, обчислювальний експеримент*

**Purpose.** To determine the patterns of stress-strain state of the frame and anchoring of the dismantling roadway when approaching the stoping.

**Methodology.** We have used the approved method of computer simulation by the finite element method. To fulfill the task we have created the three-dimensional model of layered rock massif taking into account real physical and mechanical characteristics of each lithologic layer according to the geological survey which had been carried out near the dismantling drift of the mine "Stepnaya". We have installed frame and anchor support in the roadway according to the requirements of the timbering standard. We have modeled step by step approaching of the working face. The computational experiment has been carried out in four stages at different distances from the working face to the drift.

**Findings.** We have analyzed the stress-strain state of the mounting system and established the regularities of the redistribution of stresses in the frame and anchoring support under changing distance from the working face to the roadway. The areas of stress concentration where the elements fastening system is prone to buckling failure has been defined.

**Originality.** We have established the influence of the distance to the working face on the stress-strain state of the elements of the fastening system of the dismantling roadway.

**Practical value.** The obtained results might be used for substantiation of the parameters of the fastening system of mine roadways in the area of influence of the stoping.

**Keywords:** *stoping, demolition drift, computational experiment*

*Рекомендовано до публікації докт. техн. наук В.І. Бондаренком. Дата надходження рукопису 29.04.13.*

**Baohua Yu, Chuanliang Yan, Jingen Deng, Wenliang Li, Lianbo Hu**

State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing, China, e-mail: yanchuanliang@163.com

# ROCK MECHANICAL PROPERTIES AND BOREHOLE STABILITY OF GAS SHALE

Баохуа Юй, Чуаньлян Янь, Цзіньгень Ден, Веньлян Лі, Ляньбо Ху

Державна головна лабораторія нафтових ресурсів і розвідки, Китайський університет нафти, Пекін, КНР, e-mail: yanchuanliang@163.com

# МЕХАНІЧНІ ВЛАСТИВОСТІ ТА СТІЙКІСТЬ СТІНОК СВЕРДЛОВИН ПРИ БУРІННІ НА СЛАНЦЕВИЙ ГАЗ

**Abstract.** Serious borehole instability occurs frequently during drilling in shale gas reservoirs. Shale gas reservoirs are featured by tight matrix, well-developed micro-fissures and laminations, and their peculiar mechanical properties are different from those of ordinary tight sandstones or carbonates. Thus, implementing correlative studies is of great significance to drilling and subsequent reservoir stimulation. Rock mechanical tests are performed to gas shale from south of China by the MTS-816 Rock Test System. The variation of rock mechanical properties with the angle between axial stress and the bedding plane normal (coring angle) is analyzed by the laboratory tests and a failure criterion is verified and applied to determine the strength of gas shale. The shale strength decreases first and then increases with the increasing of coring angle. It gets the maximum value with the coring angle of 0° and gets the minimum value with the coring angle of about 60°. The Young's modulus and Poisson's ratio increase with the increase of coring angle. Besides, the borehole stability model of shale gas well is established by combining transverse isotropic constitutive model and the continuously variable cohesion strength criterion. The collapse pressure is lowest when drilling to the maximum horizontal stress direction and reaches its maximum when drilling to the minimum horizontal stress direction.

**Key words:** *shale gas; rock mechanics; anisotropy; failure criterion; coring angle; borehole stability*

**Introduction.** Increasing fuel prices, the eminent fear of the limited conventional energy resources, and the projected growth of heavy industry have placed great pressure on energy supplies. As a typical representative of unconventional resources, shale gas has attracted increasing attention in recent years [1]. According to an official report from the Energy Information Administration (EIA), the risked gas in-place and technically recoverable shale gas resource are 623 and 163 tcm, respectively, which indicates that shale gas is going to play a critical and important role in the global energy market in the future.

Shale gas reservoir is characterized by clay development and laminated structure, which endows it with strong heterogeneity and anisotropy, so it is typical bedding rock and will be very likely to result in borehole collapse and downhole leakage [2]. Borehole instability can lead directly to drilling issues, such as sticking and loss of circulation. It also influences the cementing quality indirectly, and poses a potential threat to multistage fracturing. Borehole instability exists widely in shale gas reservoirs, such as Barnett shale, Marcellus shale, and Silurian shale in the Sichuan Basin. For example, at well W201-H1 in the Sichuan Basin of China, the drilling period was 72 days, and the volume of caving shale returning to the surface was as much as 35 $m^3$. Therefore, carry out mechanical test of gas shale and analysis the borehole stability has great significance for shale gas exploration and development.

**Mineral components of gas shale.** We used X-ray diffractometer (D/MAX 2500) to test mineral components of the gas shale in south of China. The results of studying 20 samples show that: There are 27,7%–46,2% of quartz with an average of 38,1% and 29,3%–46,8% of clay minerals with an average of 37,7% in the gas shale formation (Table).

*Table*

Mineral components of gas shale

| No. | Quartz/% | K-feldspar/% | Plagioclase/% | Calcite/% | Dolomite/% | Pyrite/% | Salt/% | Clay/% |
|---|---|---|---|---|---|---|---|---|
| 1-1 | 34,1 | 0,7 | 1,2 | 5,0 | 4,3 | 9,1 | | 45,6 |
| 1-2 | 38,8 | 0,5 | 1,7 | 4,3 | 4,7 | 4,2 | | 45,8 |
| 1-3 | 32,7 | | 1,2 | 4,6 | 4,2 | 15,1 | 6,6 | 35,6 |
| 1-4 | 36,1 | 1,1 | 1,4 | 4,4 | 5,2 | 10,0 | | 41,8 |
| 1-5 | 39,9 | | 2,1 | 6,2 | 4,9 | 5,8 | | 41,1 |
| 1-6 | 46,2 | | 1,8 | 5,3 | 4,0 | 5,8 | 0,8 | 36,1 |
| 1-7 | 41,1 | | 2,0 | 5,6 | 5,0 | 6,1 | | 40,2 |
| 2-1 | 37,8 | | 2,4 | 7,6 | 5,9 | 5,8 | | 40,5 |
| 2-2 | 34,1 | | 1,2 | 4,6 | 8,5 | 11,8 | 3,3 | 36,5 |
| 2-3 | 33,3 | | 1,4 | 5,6 | 5,8 | 7,1 | | 46,8 |
| 2-4 | 27,7 | | 1,2 | 6,2 | 3,9 | 18,5 | 5,9 | 36,6 |
| 2-5 | 36,3 | | 1,5 | 7,3 | 8,7 | 7,5 | | 38,7 |
| 2-6 | 43,0 | | 1,8 | 5,7 | 8,9 | 5,4 | | 35,2 |
| 2-7 | 28,5 | 0,6 | 1,5 | 6,4 | 4,2 | 18,7 | 5,1 | 35,0 |
| 3-1 | 40,7 | | 3,9 | 7,8 | 7,4 | 5,1 | | 35,1 |
| 3-2 | 45,5 | | 5,7 | 8,6 | 5,8 | 4,1 | | 30,3 |
| 3-3 | 39,0 | | 5,0 | 6,3 | 8,6 | 8,0 | | 33,1 |
| 3-4 | 38,7 | | 3,0 | 6,8 | 10,1 | 6,3 | | 35,1 |
| 3-5 | 45.6 | | 5,1 | 8,4 | 7,4 | 4,2 | | 29,3 |
| 3-6 | 43.4 | | 3,6 | 6,7 | 8,5 | 2,5 | | 35,3 |

**Microstructural characteristics of gas shale.** During the diagenetic process, with increasing depth, physical and chemical compaction of sediment is gradually replaced by gravitational compaction. The shale particle directional arranged swarming the bedding and forming obvious bedding structure [3] (Fig. 1). SEM test were taken on the gas shale. The result reveals that there are many microfractures which are very regularly oriented in gas shale (Fig. 2), and show good laminated structure.

**Rock mechanical experiments of gas shale.** The mechanical property of bedding formation is influenced by bedding plane to a great extend. In order to research the influence of bedding plane on rock mechanical properties of gas shale, core samples were obtained at fixed angels between axis and bedding plane normal, as shown in Fig. 3. Standard core samples of ϕ 25mm × 50 mm were cored with diamond coring bit. Then the samples were polished at both ends, ensure that both ends of the specimen smooth, parallel (parallelism is less than 0.01 mm of both ends) and vertical to the central axis (the angle deviation is less than 0,05°). MTS-816 Rock Test System was used in this experiment. Displacement loading mode was used with the loading rate of 1 $\mu m/s$ before the sample failed and 0,1 mm/min after failed. The loading rate of confining pressure was 3MPa/min.

*Fig. 1. Photo of gas shale*

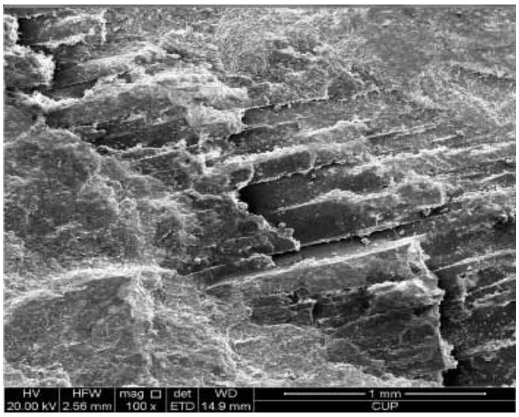



*Fig. 2. Laminated microfracture*

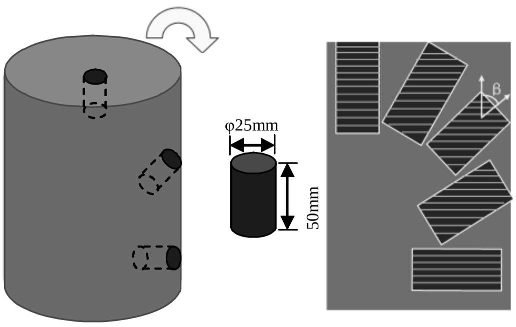



*Fig. 3. Schematic diagram of coring of gas shale*

**Strength.** The strength of gas shale is shown in Figure 4. The experimental results show that the strength of gas shale is influenced by coring angle seriously. With the same confining pressure, the strength of gas shale gets the maximum value when the coring angle is 0°. With the increasing of coring angle, the strength reduces firstly and then increasing, there is a critical angle of the minimum strength. This is common for bedding rock [4]. The gas shale gets the minimum strength with the coring angle of about 60° in this experiment. The strength with $\beta$ = 60° decreases by 60,2% compared with $\beta = 0°$ and decreases by 45,2% compared with $\beta = 90°$.

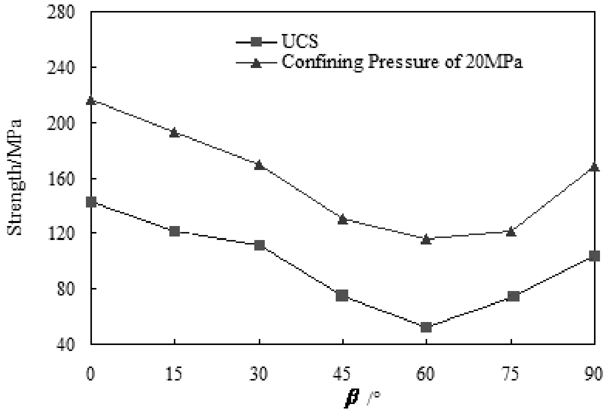



*Fig. 4. Strength versus the angle between axial stress and the bedding plane normal*

With the same coring angle, the strength of gas shale with confining pressure is higher than that tested in uniaxial compressive test. With the confining pressure of 20 MPa, the increase with $\beta = 60°$ is the largest and up to 122,7% compared with uniaxial condition. With other coring angles the increase is between 51,2%~73,5%. From the above analysis, coring angle and confining pressure has big influence on the strength of gas shale.

**Young's modulus.** Figure 5 shows the Young's modulus versus coring angle in uniaxial compressive tests. The Young's modulus of gas shale increases with the increases of coring angle. The Young's modulus is 25,9 GPa when $\beta = 0°$ and 35,5 GPa when $\beta = 90°$, with the increase of 37,1%.

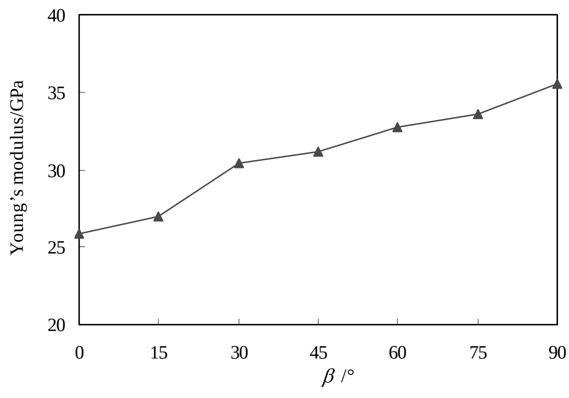



*Fig. 5. Young's modulus versus the angle between axial stress and the bedding plane normal*



ISSN 2071-2227, Науковий вісник НГУ, 2014, № 1

**Poisson's ratio.** Figure 6 shows the Poisson's ratio versus coring angle. The Poisson's ratio of gas shale increases with the increases of coring angle, which is the same with Young's modulus. The Poisson's ratio is 0,18 when $\beta = 0°$ and 0,24 when $\beta = 90°$, with the increase of 33,2%.

To describe the mechanical properties of rock with structural planes, many scholars proposed anisotropic failure criterion. As a result of our experiment, the continuously variable cohesion strength criterion developed by McLamore [5] is suitable for prediction of the strength of gas shale. And this strength criterion has been proved suitable for bedding shale in wellbore stability analysis [6]. The empirical formula is as follows

$$(\sigma_1 - \sigma_3) = \frac{2(\tau - \sigma_3 \tan\phi)}{\tan\phi - \sqrt{\tan^2\phi + 1}} ;$$

$$\begin{cases} \tau = A_1 - B_1[\cos 2(\theta - \beta)]^m, & 0° \le \beta \le \theta \\ \tau = A_2 - B_2[\cos 2(\theta - \beta)]^n, & \theta < \beta \le 90° \end{cases} ,$$

where $\sigma_1$ and $\sigma_3$ are the maximum and minimum effective principle stress, respectively. $\phi$ is the internal friction angle ; $\tau$ is cohesive force; $A_1$ = 36,4; $B_1$= 19,8 and $A_2$ = 37,1; $B_2$ = 23,2 are constants that describe the behavior of $\tau$ over the range $0° \le \beta \le \theta$ and $\theta < \beta \le 90°$, $\theta = 60°$, $\phi$ is the internal friction angle, m = 3, and n = 2.

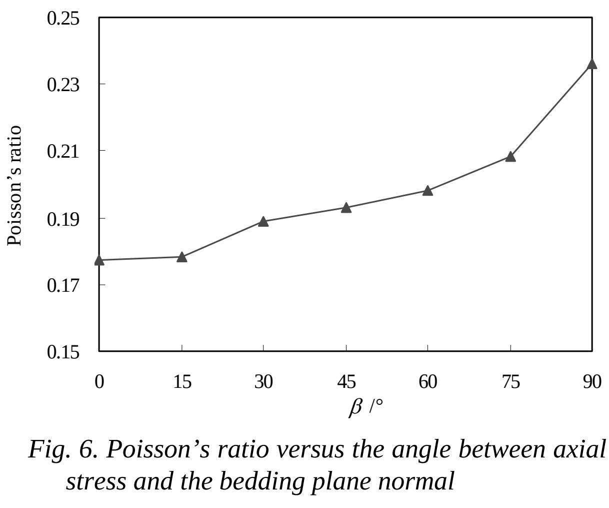


*Fig. 6. Poisson's ratio versus the angle between axial stress and the bedding plane normal*

Fig. 7 indicates that the calculation results of the McLamore empirical relationship agree well with the compressive strength of gas shale with average relative error less than 5%. The fitting curve indicates that the strength of gas shale is a function of the inclination angle between the maximum principal stress and the direction normal to the bedding plane.

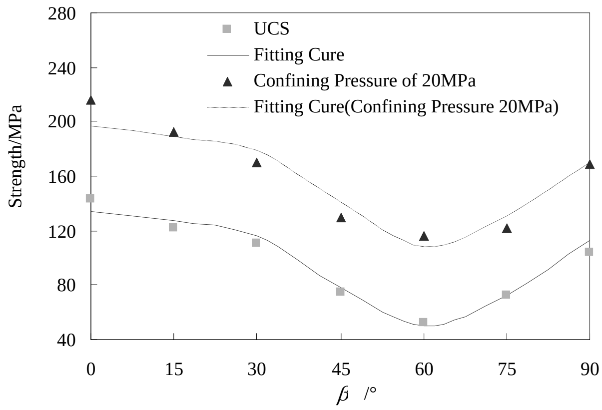


*Fig. 7. Predicted strength versus the angle between $\sigma_1$ and the bedding plane normal*

Gas shale is high in strength. Fig. 8 and Fig. 9 demonstrate the complete stress-strain curves of $\beta = 0°$ with different confining pressure. It shows brittle failure in uniaxial compressive test, and the collapsing strength, yield stress and plasticity increase with confining pressure. Define $f$ as the anisotropy index of gas shale

$$f = 1 - \frac{C_V}{C_H} ,$$

where, $C_V$ is the Young's modulus or Poisson's ratio normal to the bedding plane; $C_H$ is the Young's modulus or Poisson's ratio parallel to the bedding plane. Based on above experiments, we can obtain the anisotropy index of gas shale in south of China is 0,27 and 0,25 by Young's modulus and Poisson's ratio, respectively. The anisotropy index can evaluate the degree of anisotropy of rock, higher index means higher anisotropy.

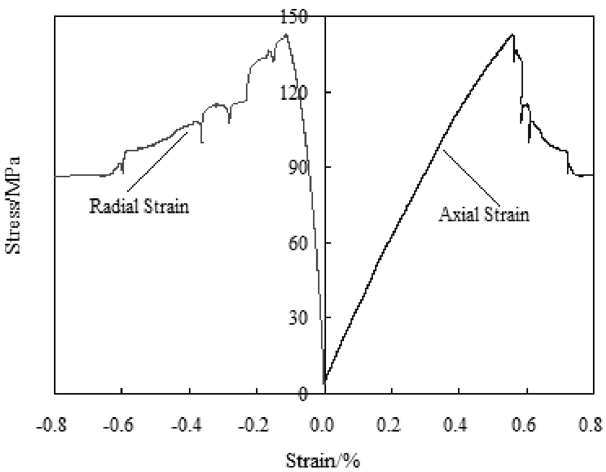


*Fig. 8. Complete stress-strain curve ( $\beta = 0°$, confining pressure of 0 MPa)*

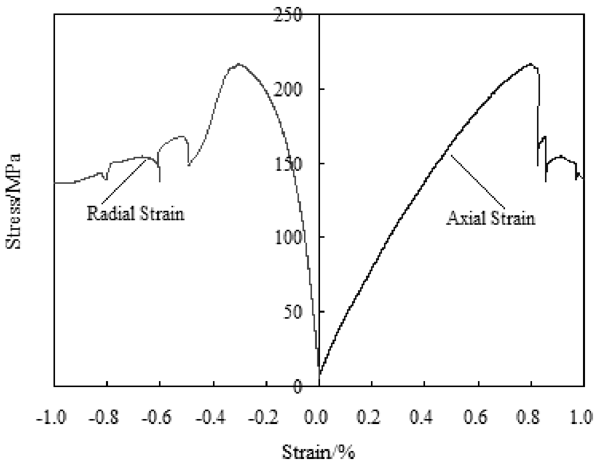


*Fig. 9. Complete stress–strain curve ( $\beta = 0°$, confining pressure of 20 MPa)*

Borehole stability analysis. Shale gas should be developed by horizontal well, and in shale formation, generally horizontal section or highly deviated well section. The mechanical model of borehole stability analysis is shown as Fig. 10.

The formation is replaced by the mud with fluid column pressure $p_{wf}$ after drilling. The original balance around the borehole is broken. Under the mud column pressure, a new balance will be built around the borehole. Without regard to the instantaneous dynamic effect when the borehole is drilled, in borehole Cartesian coordinate systems, the stress balance equation around the borehole is as following [7]

$$\sigma_{ij,j} + f_i = 0 .$$

where, $\sigma_{ij}$ is the total stress tensor, $f_i$ is the volume force of rock.

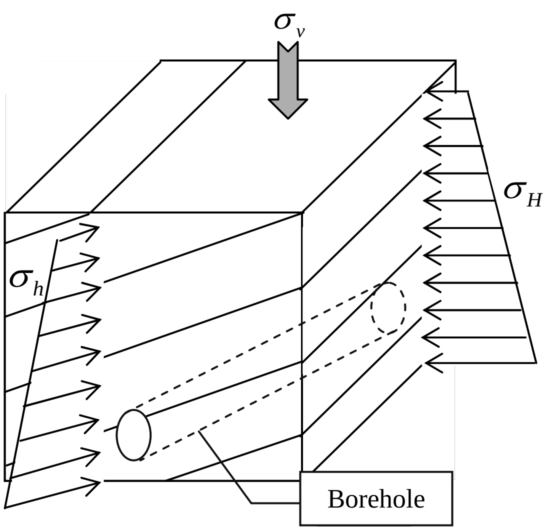


*Fig. 10. Mechanical model of shale gas well*

The boundary condition on the borehole wall is as follows [8]

$$\sigma_r = P_{wf} ,$$

where, $\sigma_r$ is the radial stress.

Under the condition of small deformation, the formation strain components and displacement components shall meet the following geometric equation [7]

$$\varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right) ,$$

where, $\varepsilon_{ij}$ is total strain tensor; $u_i$ is the displacement component.

As the main deformation and destruction of rock skeleton is controlled by effective stress, on the basis of Biot's effective stress theory, a equation can be established

$$\sigma'_{ij} = \sigma_{ij} - \alpha P_p \delta_{ij} ,$$

where, $\sigma_{ij}$ is the total stress tensor, $\sigma'_{ij}$ is the effective stress tensor, $\delta_{ij}$ is Kronecker symbol, $P_p$ is pore pressure.

Determining the constitutive equation is a basis of researching the law of deformation and failure of a borehole. Assuming the gas shale is transversely isotropic material [9], the stiffness matrix can be written as [10]

$$D_T = \begin{pmatrix} \frac{1}{E_h} & -\frac{\nu_{hh}}{E_h} & -\frac{\nu_{vh}}{E_v} & 0 & 0 & 0 \\ -\frac{\nu_{hh}}{E_h} & \frac{1}{E_h} & -\frac{\nu_{vh}}{E_v} & 0 & 0 & 0 \\ -\frac{\nu_{vh}}{E_h} & -\frac{\nu_{vh}}{E_h} & \frac{1}{E_v} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{vh}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{vh}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{2\left(1+\nu_{hh}\right)}{E_h} \end{pmatrix},$$

where $D_T$ is the stiffness matrix of transversely isotropic material.

The stiffness matrix above is defined in local coordinate system of bedding plane, but the borehole stability analysis is based on borehole coordinates. Therefore the stiffness matrix in bedding plane coordinate system needs to be transformed into that in borehole coordinate system.

$$\sigma'_{ij} = D\varepsilon_{ij} ;$$

$$D = qD_T q^T ,$$

$q$ is a transformation matrix

$$q=\begin{pmatrix} \cos^2\gamma & 0 & \sin^2\gamma & 0 & -2\sin\gamma\cos\gamma & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ \sin^2\gamma & 0 & \cos^2\gamma & 0 & 2\sin\gamma\cos\gamma & 0 \\ 0 & 0 & 0 & \cos\gamma & 0 & \sin\gamma \\ \sin\gamma\cos\gamma & 0 & -\sin\gamma\cos\gamma & 0 & \cos^2\gamma-\sin^2\gamma & 0 \\ 0 & 0 & 0 & -\sin\gamma & 0 & \cos\gamma \end{pmatrix},$$

where $\gamma$ is the angle between the normal direction of bedding plane and the wellbore axis.

According to above governing equations, stress distribution around a borehole are obtained. Combined with the continuously variable cohesion strength criterion, collapse pressure of shale gas well can be obtained.

Figure 11 shows the variation of the collapse pressure with both drilling azimuth and inclination. Computation parameters are: $P_p = 1{,}03\ SG$; $\alpha = 0{,}7$; $\sigma_H = 2{,}14\ SG$; $\sigma_h = 1{,}93\ SG$; $\sigma_v = 2{,}29\ SG$. The maximum horizontal in-situ stress direction is $N0°E$ and dip angle is 0°, while other parameters are according to experimental results.

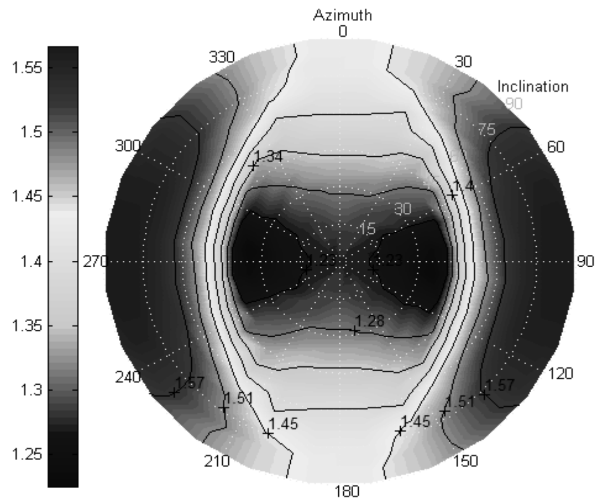


*Fig. 11. Collapse pressure versus drilling azimuth and inclination angle*

When the inclination angle is less than 45° collapse pressure with different azimuth is similar and small with a ranging from 1.21 g/cm$^3$ to 1,33 g/cm$^3$. The inclination angle has little effect on the collapse pressure and the collapse pressure is low. However, when the inclination angle is higher than 45° the collapse pressure rise sharply, especially the drilling azimuth is close to the direction of minimum horizontal in-situ stress. The collapse pressure is lowest when drilling to the maximum horizontal stress direction and reaches its maximum when drilling to the minimum horizontal stress direction. So, the risk of borehole instability is the highest when drilling to the minimum horizontal stress direction.

**Conclusions.**

1. Gas shale in south of China shows good laminated structure, and the most mineral components of gas shale is quartz and clay minerals.

2. The continuously variable cohesion strength criterion is suitable for prediction of the strength of gas shale. The strength decreases first and then increases with the increasing of coring angle. It gets the maximum value with the coring angle of 0° and gets the minimum value with the coring angle of about 60°. The maximum decreasing range of shale strength is up to 60,2%. The Young's modulus and Poisson's ratio increase with the increases of coring angle.

3. Borehole instability of shale gas well is caused by redistribution of in-situ stresses near the borehole in an anisotropic formation. The collapse pressure is lowest when drilling to the maximum horizontal stress direction and reaches its maximum when drilling to the minimum horizontal stress direction.

4. More attention should be given when drilling horizontal wells near the direction of minimum horizontal in-situ stress in shale gas reservoirs, because the collapse pressure is higher in this region

Acknowledgments. This work is financially supported by Science Fund for Creative Research Groups of the National Natural Science Foundation of China (Grant No. 51221003), National Natural Science Foundation Project of China (Grant No. 51174219) and National Oil and Gas Major Project of China (Grant No. 2011ZX05009-005).

**References / Список літератури**

**1.** Zou, C., Dong, D., Wang, S., Li, J., Li, X., Wang, Y. and Cheng, K. (2010), "Geological characteristics and resource potential of shale gas in China", *Petroleum exploration and development*, vol. 37, no.6, pp. 641–653.

**2.** Narayanasamy, R., Barr, D. and Milne, A. (2010), "Wellbore Instability Predictions within the Cretaceous Mudstones, Clair Field, West of Shetlands", *SPE Drilling & Completion*, vol. 25, no.4, pp. 518–529.

**3.** Suarez-Rivera, R., Green, S., Handwerger, D., Martin, W. and Kieschnick, J. (2005), "Accounting for Heterogeneity Provides a New Perspective for Completions in Tight Gas Shales", In Alaska Rocks 2005, *The 40th US Symposium on Rock Mechanics (USRMS)*.

**4.** Mao, H.J. and Yang, C.H. (2005), "Study on effects of discontinuities on mechanical characters of slate", *Chinese Journal of Rock Mechanics and Engineering*, vol. 24, no. 20, pp. 3651–3656.

**5.** McLamore, R. and Gray, K.E. (1967), "The mechanical behavior of anisotropic sedimentary rocks", *Journal of Engineering for Industry*, Translation of the A.S.M.E., vol. 89, pp. 62–73.

**6.** Yuan, J.L., Deng, J.G., Tan, Q., Yu, B.H. and Jin, X.C. (2012), "Borehole Stability Analysis of

Horizontal Drilling in Shale Gas Reservoirs", *Rock Mechanics and Rock Engineering*, in press.
**7.** Xu, Z.L. (1998), [Elastic Mechanics], Beijing, Higher Education Press.
**8.** Deng, J.G. (1997), "Calculation method of mud density to control borehole closure rate", *Chinese Journal of Rock Mechanics and Engineering*, vol. 16, no. 6, pp. 522–528.
**9.** Khan, S., Williams, R., Ansari, S. and Khosravi, N. (2012), "Impact of Mechanical Anisotropy on Design of Hydraulic Fracturing in Shale", *In Abu Dhabi International Petroleum Conference and Exhibition*, Abu Dhabi, UAE.
Hornby, B.E. (1998), "Experimental laboratory determination of the dynamic elastic properties of wet, drained shale", *Journal of Geophysical Research*, vol. 103, no. B12, pp. 29945–29964.

При бурінні у продуктивних горизонтах, що містять сланцевий газ, часто виникають ускладнення, обумовлені порушенням стійкості стінок свердловин. Газовмісні породи відрізняються високою щільністю, добре розвиненою мікротріщинуватістю й шаруватістю, і їх механічні властивості відмінні від властивостей щільних піщаників або карбонатів. Таким чином, проведення порівняльних досліджень має велике значення для буріння свердловин і розкриття продуктивних пластів. За допомогою системи визначення властивостей гірських порід MTS-816 Rock Test System проведено дослідження механічних властивостей горючого сланцю, що видобувається на півдні Китаю. У лабораторних умовах проведені дослідження зміни механічних властивостей у залежності від кута між осьовим навантаженням і нормаллю площини нашарування (кут відбору керна), критерій оцінки руйнування був перевірений і застосований для визначення міцності горючих сланців. Зі збільшенням кута відбору керна міцність сланцю спочатку зменшується, а потім збільшується. При куті відбору керна 0° вона досягає максимального значення, а при куті керна біля 60° – мінімального. Модуль Юнга та коефіцієнт Пуассона зростають зі збільшенням кута відбору керна. Крім того, проведено моделювання стабільності стінок свердловини, що буриться в горючому сланці шляхом об'єднання трансверсальної ізотропної моделі стану та критерію плавнорегульованої когезійної міцності. Навантаження руйнування має найменше значення при бурінні в напрямку максимальної горизонтальної напруги й досягає максимуму при бурінні в напрямку мінімальної горизонтальної напруги.

**Ключові слова:** *сланцевий газ, механіка гірських порід, анізотропія, критерій руйнування, кут відбору керна, стійкість ствола свердловини*

При бурении в продуктивных горизонтах, содержащих сланцевый газ, часто возникают осложнения, обусловленные нарушением устойчивости стенок скважин. Газосодержащие породы отличаются высокой плотностью, хорошо развитой микротрещиноватостью и слоистостью, и их механические свойства отличны от свойств плотных песчаников или карбонатов. Таким образом, проведение сравнительных исследований имеет большое значение для бурения скважин и вскрытия продуктивных пластов. С помощью системы определения свойств горных пород MTS-816 Rock Test System проведено исследование механических свойств горючего сланца, добываемого на юге Китая. В лабораторных условиях проведены исследования изменения механических свойств в зависимости от угла между осевой нагрузкой и нормалью плоскости напластования (угол отбора керна), критерий оценки разрушения был проверен и применен для определения прочности горючих сланцев. С увеличением угла отбора керна прочность сланца сначала уменьшается, а затем увеличивается. При угле отбора керна 0° она достигает максимального значения, а при угле керна около 60° – минимального. Модуль Юнга и коэффициент Пуассона возрастают с увеличением угла отбора керна. Кроме того, проведено моделирование стабильности стенок скважины, буримой в горючем сланце путем объединения трансверсальной изотропной модели состояния и критерия плавнорегулируемой когезионной прочности. Нагрузка разрушения имеет наименьшее значение при бурении в направлении максимального горизонтального напряжения и достигает максимума при бурении в направлении минимального горизонтального напряжения.

**Ключевые слова:** *сланцевый газ, механика горных пород, анизотропия, критерий разрушения, угол отбора керна, устойчивость ствола скважины*

*Рекомендовано до публікації канд. техн. наук А.К. Судаковим. Дата надходження рукопису 29.04.13.*