Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 14 (1): 33-39, 2014
ISSN 1812-5654 / DOI: 10.3923/jas.2014.33.39

Wellbore Stability Research of Heterogeneous Formation

Yuan Cao and Jingen Deng
State Key Laboratory of Petroleum Resource and Prospecting,
China University of Petroleum, Beijing, China

Abstract: The shale of deep formation are often heterogeneous and exist in the form of beddings. Their strength vary with bedding dip. Sever wellbore instability will occur if the properties are neglected while drilling. Strength tests at different levels of confining pressure had been done by use of formation and artificial bedding cores cutting at different bedding dip angles. Theoretical strength of the cores were calculated by three typical anisotropic criterions. Experimental data demonstrated that their strength decreased firstly and then increased with bedding dip increasing. The lowest strength values occur at 45-65°. Theoretical values calculated by Variable Cohesion and Friction Angle criterion (VCFA) agreed with the test results. Compared to isotropic criterion, the highest sloughing mud density of wellbore calculated by VCFA was larger by about 0.3 g cm^{-3}. The borehole was most prone to collapse at 45- 65° inclination. The research results were demonstrated by filed application. Sloughing mud density of bedding formation should be calculated by VCFA. Well trajectory in bedding formation should be carefully designed.

Key words: Wellbore stability, anisotropy, bedding, strength criterion

INTRODUCTION

Wellbore instability is a challenge problem of drilling well in the world. Natural rock is often heterogeneous (Duveau *et al*., 2001). Borehole sloughing will occur if the anisotropic properties are neglected which are mainly caused by discontinuous structures, such as bedding, stratification, layering, foliation and fracture. These weakly cemented structures are sensitive to the normal stresses direction.

Anisotropic strength criterions are important for precisely describing strength characteristics of heterogeneous rock and are investigated by many researchers, such as (Jeager, 1960; Mcclintock and Walsh, 1963; Walsh and Brace, 1964; Hobbs, 1964; Donath, 1964; McLamore and Gray, 1967; Attewell and Sandford, 1974; Hoek and Brown, 1980; Zhou *et al*., 1992; Yasar, 1995; Amadei, 1996; Sheorey, 1997; Chen *et al*., 1998).

Cohesion and internal friction angle are two important parameters for shale strength (Ewy and Bovberg, 2010). Cohesion caused by interaction force among particles is the shear strength when the normal stress is zero which is static force and only exists before failure occurrence. Internal friction angle is subjected to roughness concentration of mutual sliding surfaces which is dynamic force and exists in the failure process.

Three anisotropic criterions with different descriptions of cohesion and internal friction angle are compared to determine the optimum method of characterizing heterogeneous rock strength:

- Single plane of weakness criterion (SPW, Jeager, 1960)
- Variable Cohesion Force criterion (VCF, Jeager, 1960)
- Variable Cohesion and Friction Angle criterion (VCFA, McLamore and Gray, 1967)

Artificial bedding cores and formation bedding cores are selected to do uniaxial and triaxial strength tests. The three above criterions are used to fit the test data and calculate the sloughing mud density.

Methodology: Artificial cement cores and formation cores of Sichuan Basin and Beibuwan Basin with bedding characteristics were selected to test their strength. The bedding dip angles of cores were, respectively 0, 10, 20, 30, 40, 50, 60, 70, 80 and 90 degree. The confining pressures of experiments are, respectively 0, 5, 10 Mpa. Also, theoretical strength of the cores were calculated by SPW, VCF and VCFA. The optimal strength criterion was selected through comparison of test data and calculated values. At borehole inclination 0-90° and stress orientation N30°E (maximum principle stress

Corresponding Author: Yuan Cao, State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing, 18 Fuxue Road, Changping City, 102249, Beijing Province, People's Republic of China Tel: +86-10-8973391-21

direction)- N120°E (minimum principle stress direction), sloughing mud densities of wellbore were calculated by the above three criterions and Mohr-Coulomb criterion (isotropic criterion). Calculated results were compared and filed applications were provided.

ANISOTROPIC CRITERION

Cohesion (C) and internal friction angle (ϕ) are not constant in anisotropic strength criterion. The three criterions (SPW, VCF, VCFA) have different descriptions of C and ϕ.

SINGLE PLANE OF WEAKNESS CRITERION(SPW)

According to SPW, there are one set of parallel beddings in heterogeneous rock. Rock matrix and beddings have different values of C and ϕ. The beddings and matrix strength are expressed respectively by Eq. 1 and 2. The bedding will be failure when β is larger than ϕ and smaller than $\pi/2$. Otherwise the rock matrix will be destroyed:

$$\sigma_1 - \sigma_3 = \frac{2(C' + \sigma_3 \mu')}{(1 - \mu' \cot\beta)\sin 2\beta} \quad (1)$$

$$\sigma_1 - \sigma_3'' = 2(C + \sigma_3''\mu)\left[(\mu^2+1)^{1/2} + \mu\right] \quad (2)$$

Where:
μ, μ' = Internal friction coefficient, equal to tanϕ, tanϕ'
σ_1 = Maximum principal stress
σ_3 = Minimum principal stress

VARIABLE COHESION FORCE CRITERION (VCF)

C in VCF given by Eq. 3 varies with β and is calculate by Eq. 4:

$$\left(\sigma_1 - \sigma_3''\right) = \frac{2(C + \sigma_3''\mu)}{\mu - \sqrt{1+\mu^2}} \quad (3)$$

$$C = A - B\cos(2(\alpha - \beta)) \quad (4)$$

Where:
α = The value of β while the rock strength is lowest
A, B = Constants determined by rock physical characteristics

VARIABLE COHESION AND FRICTION ANGLE CRITERION (VCFA)

C and ϕ of VCFA given by Eq. 5 all change with β and are expressed as Eq. 6:

$$\sigma_1 - \sigma_3'' = \frac{C + 2\sigma_3''\mu}{\sqrt{\mu^2 + 1} - \mu} \quad (5)$$

$$\begin{cases} C = A_2 - B_2\left[\cos 2(\alpha - \beta)\right]^m, \alpha < \beta \le 90° \\ C = A_2 - B_2\left[\cos 2(\alpha - \beta)\right]^m, \alpha < \beta \le 90° \\ \mu = C_1 - D_1\left[\cos 2(\alpha' - \beta)\right]^n, 0° \le \beta \le \alpha' \\ \mu = C_2 - D_2\left[\cos 2(\alpha' - \beta)\right]^n, \alpha' < \beta \le 90° \end{cases} \quad (6)$$

Where:
A_1, A_2, B_1, B_2, C_1, C_2, D_1, D_2 = Constant determined by rock physical characteristics
m = Cohesive index
n = Internal friction angle index

SAMPLE DESCRIPTION AND TEST METHOD

As there is no ideal parallel bedding rock in nature, cement cores with parallel beddings are made in laboratory. The manufacture mould is shown in Fig. 1.

Cement paste have been put into the mould layer by layer with the thickness being about 2-3 mm. The surfaces of layers are planar and parallel to each other. There is a piece of permeable paper put between two layers. Artificial bedding sample is completed until the paste become hard.

Meanwhile, formation bedding shale of Sichuan Basin and Beibuwan Basin of China are selected. The clay mineral compositions are show in Table 1.

Test cores are cut in the cement and shale samples. The cutting angle between core axial direction and bedding normal direction is β as shown in Fig. 2. Cores of size 25 mm diameter by length 50 mm are cut at the degree of β being 0, 10, 20, 30, 40, 50, 60, 70, 80 and 90°.

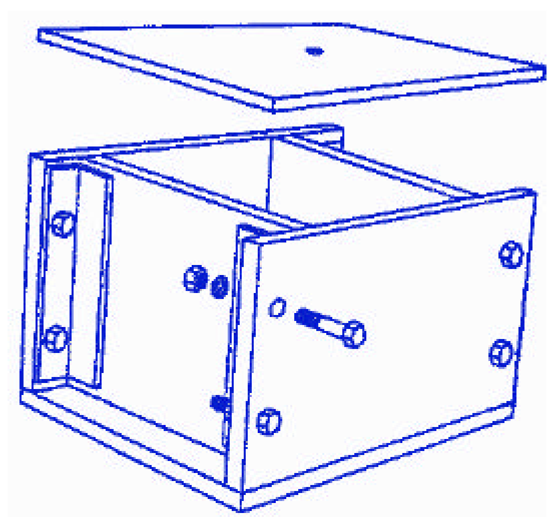

Fig. 1: Bedding cement sample manufacture mould

Table 1: Content of clay mineral of Sichuan Basin and Beibuwan Basin

		Content of clay mineral/ (%)					I/S mixed-layer rate (%)	
Sample areas	Depth	Smectite	Illite	Kaolinite	Chlorite	I/S	Smectite	Illite
Sichuan Basin	2310	0	32	14	17	37	20	80
Beibuwan Basin	3125	0	47	17	19	17	10	90

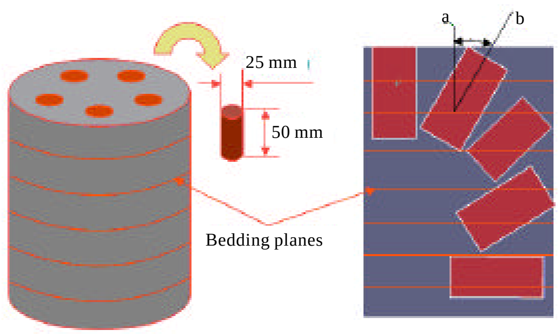

Fig. 2: Cutting way of cores in bedding sample

The cores are used to do strength test by 816 Rock Test System made by MTS. The test values of confining pressure are, respective 0, 5 and 10 Mpa.

EXPERIMENT RESULTS AND ANALYSIS

Experiment result: The test results of cement cores, Sichuan Basin and Beibuwan Basin shale cores are respectively plot in Fig. 3.

The three anisotropic criterions (SPW, VFC, VCFA) mention above are used to calculate the theoretical uniaxial compressive strength of different cores as shown in Fig. 4.

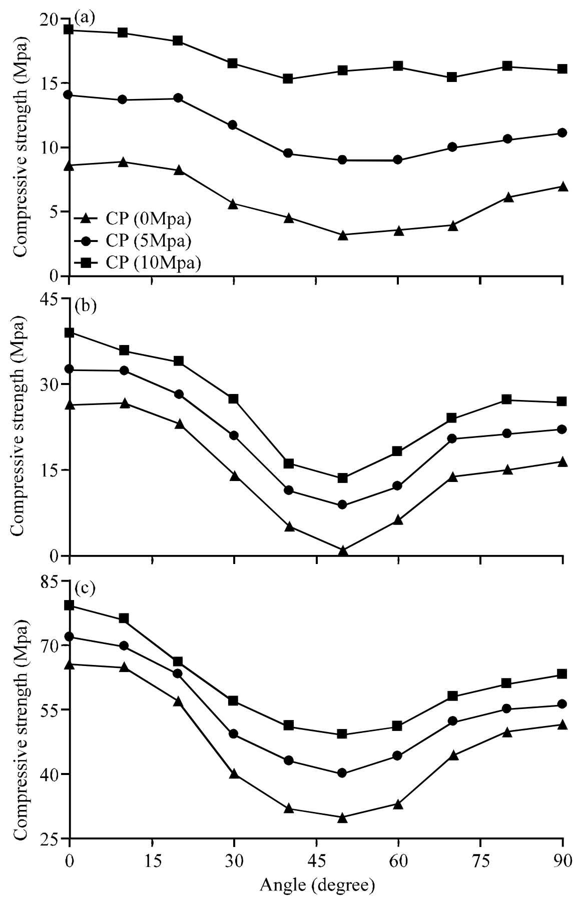

Fig. 3(a-c): Experimental compressive strength on different confining pressure (CP) of cores cutting in different bedding dip angles (a) Cement cores (b) Beibuwan Basin shale cores and (c) Sichuan Basin shale cores

DISCUSSION

It can be seen from Fig. 3 that the strength of bedding cores varies with bedding inclination which demonstrate that beddings have an important influence on anisotropy rock strength. Moreover, the differences of the maximum and the minimum at specific confining pressure decrease with increase of confining pressure and the anisotropy rock tend to be isotropy.

It can be seen from Fig. 4 that the UCS is fitting very well by SPW. When β is smaller than ϕ, the rock matrix is failure and the UCS do not vary with β. Test data of Beibuwan Basin and Sichuan Basin shale cores are fitting very well by VCFA. The rock strength always vary with β. When β is in the degree boundary 15-75°, UCS diversification is severe. Out of the boundary, the diversification is gentle.

Jeager (1960) has introduction two methods (SPW and VCF) to description rock isotropic characteristic. According to SPW criterion, the weak structural bedding will be destroyed when the bedding inclinations are in the suitable angel boundary and experimental results with ideal parallel beddings cement cores have demonstrated the theory. However, the beddings of natural shale rock are not completely parallel, VCF criterion recognize the cohesion of rock is not constant and varies with the bedding inclination Eq. 4. Compared to the experimental result, the variation degree of UCS calculated by VCF criterion have been overestimated at the angles nearby 0 and 90°. VCFA criterion developed by McLamore and Gray (1967) correctly give the variation law of cohesion and internal friction angle and the theoretical value and test results of UCS are similar in all the angle boundary (0-90°).

SIMPLIFICATION OF VCFA

Compared to the other two anisotropic criterions, VCFA can precisely calculate the strength change. However, there are too many parameters in VCFA which lead to the equation complex.

Diversification of C and ϕ introduce lots of constants and the equation of the two parameters are similar. m and n are assigned different numbers to compare their influence degree on rock strength. The detail is shown in Fig. 5.

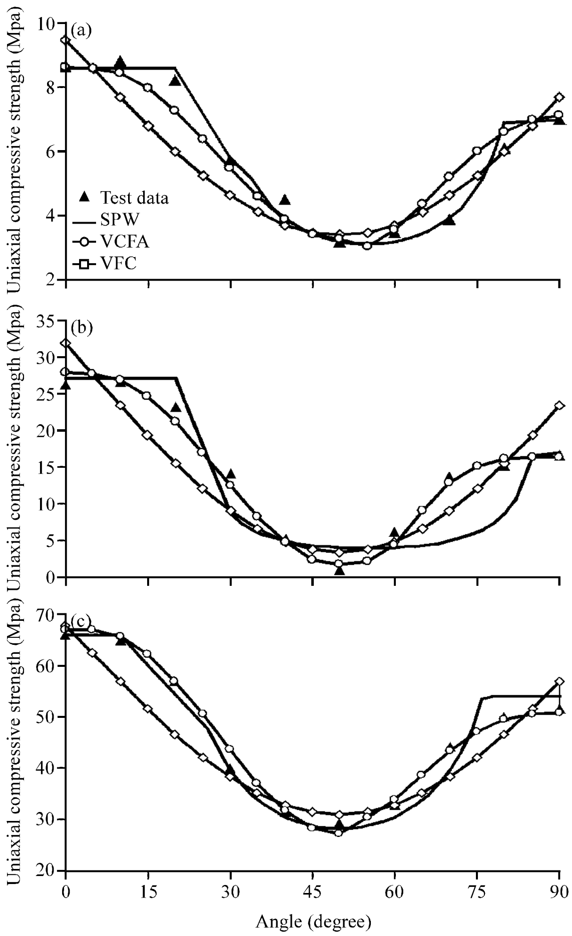

Fig. 4(a-c): Uniaxial compressive strength test data and theoretical values respectively calculated by the strength criterions SPW, VFC and VCFA of cores cutting in different bedding dip angles (a) Cement cores (b) Beibuwan Basin shale cores and (c) Sichuan Basin shale cores

Make the curve marked by m = 3 and n = 3 as a comparison, the curve marked by m = 1 and n = 3 is below the curve marked by m = 3 and n = 6 and the curve marked by m = 3 and n = 1 is above the C curve marked by m = 3 and n = 6. So the affection degree on rock strength of m is larger than n. The equations of ϕ in Eq. 6 are leaved out, meanwhile, n replaces m in equations of C when $\alpha<\beta\leq 90°$. As a result, Eq. 6 is simplified to Eq.7:

$$\begin{cases} C = A_2 - B_2\left[\cos 2(\alpha-\beta)\right]^m, \alpha<\beta\leq 90° \\ C = A_2 - B_2\left[\cos 2(\alpha-\beta)\right]^n, \alpha<\beta\leq 90° \end{cases} \quad (7)$$

VCFA with Eq. 7 is called simplify VCFA(SVCFA). The UCS of Sichuan Basin cores and fitted curves by VCFA and SVCFA are plotted in Fig. 6. The calculated results by VCFA and SVCFA are similar, so VCFA can be instead by SVCFA.

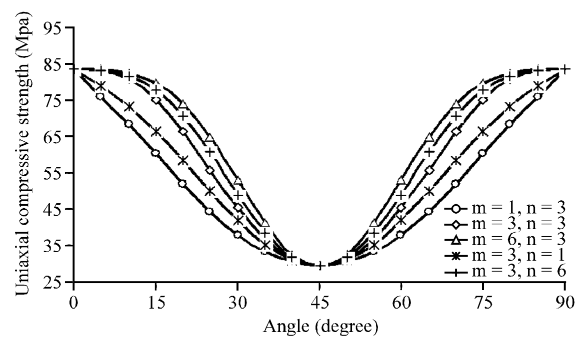

Fig. 5: Theoretical uniaxial compressive strength of cores cutting in different bedding dip angles calculated by VCFA strength criterion (Eq. 5 and 6) with different values of cohesive index (m) and internal friction angle index (n)

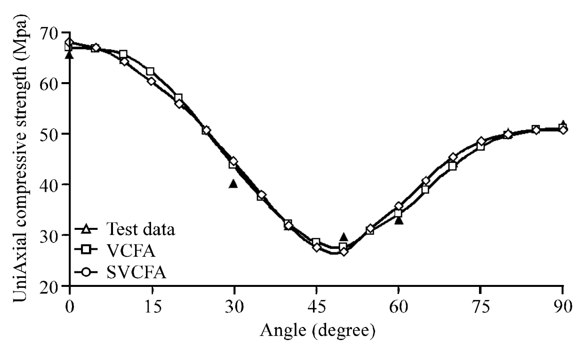

Fig. 6: Uniaxial compressive strength test data and theoretical values respectively calculated by strength criterions VCFA and SVCFA of Sichuan Basin shale cores cutting in different bedding dip angles

WELLBORE STABILITY RESEARCH OF BEDDING FORMATION

Sloughing mud density calculated model: Principal stresses of virgin formation can be obtained by well log data, such as vertical stress (σ_v), maximum horizontal stress (σ_H) and minimum horizontal stress (σ_h). A coordinate system (x', y', z') is oriented where the z'-axis is parallel to the direction of σ_v. The stresses in the vicinity of deviated wellbore are most conveniently described in a coordinate system (x, y, z) where the z-axis is parallel to the wellbore. So it is necessary to transform the principal stresses form (x', y', z') to (x, y, z). (Chen *et al*., 1998) has described the transformation details.

A hypothesis has been made that the borehole wall is impermeable and the stresses on the wall can be expressed as Eq. 8:

$$\begin{cases}\sigma_r = p \\ \sigma_\theta = -p + \sigma_{xx}(1-2\cos 2\theta) + \sigma_{yy}(1+2\cos 2\theta) - 4\sigma_{xy}\sin 2\theta \\ \sigma_z = \sigma_{zz} - \mu\left[2(\sigma_{xx}-\sigma_{yy})\cos 2\theta + 4\sigma_{xy}\sin 2\theta\right] \\ \sigma_{r\theta} = 0 \\ \sigma_{rz} = 0 \\ \sigma_{\theta z} = -2\sigma_{xz}\sin\theta + 2\sigma_{yz}\cos\theta\end{cases} \quad (8)$$

It can be seen from Eq. 8 that θ-z plane is the failure plane and σ_r is a principle stress. Eq. 9 describes the normal stress σ and the shear stress τ of θ-z plane:

$$\begin{cases}\sigma = \sigma_\theta\cos^2\gamma + 2\sigma_{\theta z}\cos\gamma\sin\gamma + \sigma_z\sin^2\gamma \\ \tau = \dfrac{1}{2}(\sigma_z - \sigma_\theta)\sin 2\gamma + \sigma_{\theta z}\cos 2\gamma\end{cases} \quad (9)$$

Where:

γ = The angle between the axis z (σ_z direction) and the failure plane as show in Fig. 7

When dσ/dγ = Two values of γ can be obtained as show in Eq. 10:

$$\begin{cases}\gamma_1 = \dfrac{1}{2}\arctan\dfrac{2\sigma_{\theta z}}{\sigma_\theta - \sigma_z} \\ \gamma_2 = \dfrac{\pi}{2} + \dfrac{1}{2}\arctan\dfrac{2\sigma_{\theta z}}{\sigma_\theta - \sigma_z}\end{cases} \quad (10)$$

Two principal stress of the failure plane can be obtained by calculating Eq. 9 with γ_1 and γ_2, as show in Eq. 11:

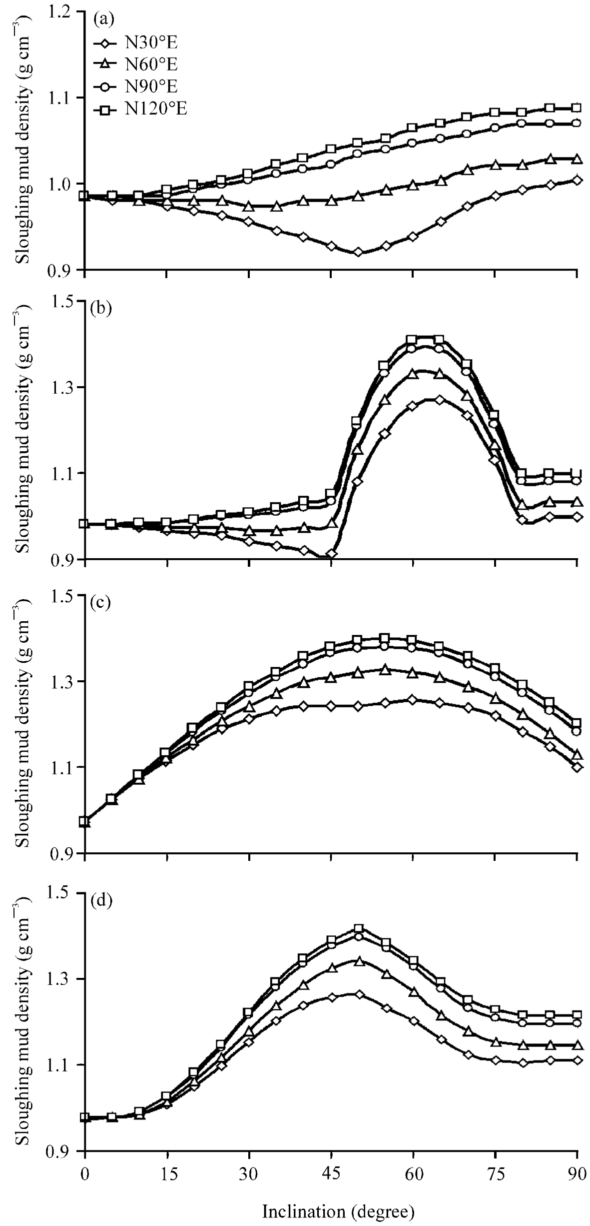

Fig. 7(a-d): Borehole sloughing mud densities at different inclination degrees and stress orientation (from maximum to minimum principle stress direction) calculated by strength criterions (a) Mohr-Coulomb, (b) SPW, (c) VCF and (d) VCFA

$$\begin{cases}\sigma_1 = \dfrac{\sigma_z + \sigma_\theta}{2} + \sqrt{\left(\dfrac{\sigma_z - \sigma_\theta}{2}\right)^2 + \sigma_{\theta z}^2} \\ \sigma_2 = \dfrac{\sigma_z + \sigma_\theta}{2} - \sqrt{\left(\dfrac{\sigma_z - \sigma_\theta}{2}\right)^2 + \sigma_{\theta z}^2}\end{cases} \quad (11)$$

Then, the strength criterions can be used directly to determine that weather the wellbore is failure and calculate the Sloughing Mud Density (SMD).

SLOUGHING MUD DENSITY ANALYSIS

SMD of deviated well at 0-90° inclination are, respectively calculated by Mohr-Coulomb criterion, SPW, VFC and VCFA. The parameters used in the calculation are: v = (poisson ratio), ϕ = 36°, α = 50°, σ_v = 2.4 g cm^3, σ_h = 2.2 g cm^3, ρ_p = 1.7 g cm^3, ρ_p=1.0 g cm^3 (pore pressure gradient), the direction of the maximum principle stress is N30°E (the angle turn east from the north direction).

Calculated results are shown in Fig. 7. As the results are axial symmetry, SMD are only shown quarter of borehole wall from the maximum principle stress direction (N30°E) to the minimum principle stress direction (N120°E).

Mohr-Coulomb criterion is a typical isotropic cricterion and used widely at wellbore stability calculation. Make comparison of the isotropic criterion and the anisotropic criterions, some items for drilling guidance can be obtained.

The peak SMD of isotropic criterion is much lower than that of anisotropic criterions, the difference is about 0.3 g cm^3 in the above calculation case. If the SMD calculated by the isotropic criterion are selected for near-balance drilling, sever sloughing are prone to occurrence with the increase of inclination.

The SMD in horizontal borehole is larger than that in deviated section by isotropic criterion, meanwhile, the peak SMD of anisotropic criterions exist at the 45-65° inclination degree. Also, SMD gradually decrease from maximum principle stress direction to minimum principle stress direction. So mud density should be weight to the biggest value before 45° inclination and it will be too late to weight mud density before drilling the horizontal section. Also thec drilling azimuth should be at the maximum principle stress direction.

Make comparison of the three anisotropic criterions, in addition to SMD of the horizontal section calculated by SPW, SMD of the vertical borehole, the horizontal borehole and the peak value are similar to each other. However, in the process of inclination change, SMD calculated by SPW are smaller and VCF calculated results are larger than SMD of VCFA. If mud density is lower than actual SPW, borehole surface is prone to collapse and mud will invade the inner bedding and fracture, sever borehole sloughing is going on its way. On the other hand, if mud density is larger than actual SPW, the fragile weak cement beddings are easily fractured and sever lost circulation will occur. SMD for bedding formation should be precisely calculated and controlled while drilling.

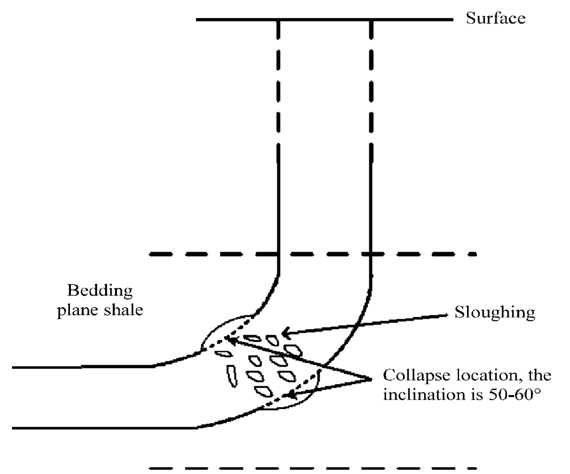

Fig. 8: Borehole of X1 well sloughed at 50-60° inclination and the lithology of sloughing rock was bedding shale

FIELD APPLICATION

X1 well is a horizontal shale gas well in Sichuan Basin of China and the TD is 2823 m. The shale reservoir has obvious bedding characteristic. SMD is 1.22-1.45 g cm^3 calculated by isotropic criterion and is 1.22-1.58 g cm^3 calculated by anisotropic criterion. The difference between the two peak SMD is 0.13 g cm^3. Sever borehole sloughing has occurred while drilling at 50-60° inclination (Fig. 8) by use of mud with density being 1.47 g cm^3. The adjacent X2 well had a similar wellbore configuration with X1 well. The deviated section was drilling by mud density of 1.60 g cm^3, the process was smooth and there was no borehole instability occurrence.

CONCLUSION

Strength characteristics of anisotropic rock are significant different from that of isotropic rock. Bedding planes are common weakly cemented structures in shale and coal which severely affect their strength. Cohesion and internal friction are two important parameters. The former influence on strength is larger than the latter demonstrated by numerical simulation.

Artificial bedding cores and formation bedding cores are selected to run strength tests in different confining pressure. VCFA is the most appropriate one among the three anisotropic criterions to fit the laboratory tests data and calculate the formation bedding rock strength.

A method has been developed to calculate sloughing mud weight by strength criterions. SMD of bedding rock calculated by isotropic criterion is lower than the actual SMD. Among the three anisotropic criterions, the calculated result of VCFA is the best one to fit the field experience very well. When the borehole inclination is small (less than 10° in the article case) and large (more than 80° in the article case), the SMD is almost constant. Between the two inclination values, the SMD change sharply and reach peak at one middle value (50° in the article case).

According to the research results, some advise have been given for safety drilling bedding formation: Mud density should be controlled precisely to prevent borehole sloughing or bedding fracturing; borehole azimuth should be at the maximum principle stress direction; mud density should be weight before drilling the inclination of peak SMD; borehole in the large SMD inclination boundary should be as short as possible to avoid wellbore instability.

REFERENCES

Amadei, B., 1996. Importance of anisotropy when estimating and measuring *in situ* stresses in rock. Int. J. Rock Mech. Mining Sci. Geomech. Abstr., 33: 293-325.

Attewell, P.B. and M.R. Sandford, 1974. Intrinsic shear strength of a brittle, anisotropic rock-I: Experimental and mechanical interpretation. Int. J. Rock Mech. Mining Sci. Geomech. Abstr., 11: 423-430.

Chen, C.S., E. Pan and B. Amadei, 1998. Determination of deformability and tensile strength of anisotropic rock using Brazilian tests. Int. J. Rock Mech. Mining Sci., 35: 43-61.

Donath, F.A., 1964. Strength Variation and Deformational Behaviour in Anisotropic Rocks. In: State of Stress in the Earth's Crust, Judd, W.R. (Ed.). Elsevier Publishing Co., New York, USA., pp: 281-298.

Duveau, G., Y. Tiantang and J.F. Shao, 2001. Modeling of Anisotropy in Elastoplastic Sedimentary Rocks. In: Rock Mechanics in the National Interest, Elsworth, D., J.P. Tinucci and K.A. Heasley (Eds.). A.A. Balkema, Amsterdam, The Netherlands, ISBN-13: 9789026518362, pp: 1517-1522.

Ewy, R.T. and C.A. Bovberg, 2010. Strength anisotropy of mudstones and shales. Proceedings of the 44th U.S. Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, June 27-30, 2010, Salt Lake City, Utah, USA.

Hobbs, D.W., 1964. The tensile strength of rocks. Int. J. Rock Mech. Mining Sci. Geomech. Abstr., 1: 385-388.

Hoek, E. and E.T Brown, 1980. Underground Excavations in Rock. MAA Publishing Company, London.

Jeager, J.C., 1960. Shear failure of anisotropic rocks. Geol. Mag., 97: 65-72.

McLamore, R. and K.E. Gray, 1967. The mechanical behavior of anisotropic sedimentary rocks. J. Eng. Ind., 89: 62-73.

Mcclintock, F.A. and J.B. Walsh, 1963. Friction on griffith cracks in rocks under pressure. Proceedings of 4th US National Congress of Applied Mechanics, June 18-21, 1962, University of California, Berkeley, CA., USA., pp: 1015-1021.

Sheorey, P.R., 1997. Empirical Rock Failure Criteria. A.A. Balkema, Netherlands, ISBN-13: 9789054106708, Pages: 176.

Walsh, J.B. and W.F. Brace, 1964. A fracture criterion for brittle anisotropic rock. J. Geophys. Res., 69: 3449-3456.

Yasar, E., 1995. The properties and classification of anisotropic rocks. Ph.D. Thesis, University of Nottingham, UK.

Zhou, D.Q., X.S. Liu and Q. Lin, 1992. Strength criteria for anisotropic rocks and experimental studies: 25302-MS. Society of Petroleum Engineers. http://www.onepetro.org/mslib/app/Preview.do?paper Number=0002530 2&societyCode=SPE