Establishment and Application of Horizontal In-situ Stress Inversion Model in Coal Rock based on Multiple Well Fracture Data

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Abstract

It was difficult to obtain horizontal in-situ stress values in methane reservoir, restricted by many factors. Being an important stimulate treatment, hydraulic fracturing offered plenty of data for researching and analyzing reservoir property. An overdetermined equation about fracture pressure and horizontal in-situ stress was established based on analyzing stress distribution on borehole wall and deducing definite formation of fracture pressure. In-situ stress inversion model was given with some settle on the equation set, such as variables separation, derivation. Horizontal in-situ stresses of south Shizhuang were given based on the inversion model, result as: Overburden pressure similar with horizontal in-situ stresses in this area, and difference value under 3MPa among the three stresses; Minimum horizontal in-situ stress value was the smallest three in-situ stresses; Monitoring results of closure stresses slightly higher than minimum in-situ stress. The simulate results of in-situ stresses match with fracture monitoring, closure data and theory. This article could be used for reference and offered effective data for CBM exploitation.

Keywords

Hydraulic Fracture; Fracture Pressure; Horizontal In-situ Stress; Inversion Model; Overdetermined Equation.

1. Introduction

The measurement of coal seam in-situ stress plays an important role in the exploration, development and production of coal-bed methane. At present, the measurement of in-situ stress is mainly divided into indoor test, field test and empirical prediction methods[1-3]. However, due to the constraints of domestic exploration and development costs and other factors[4], the method of obtaining in-situ stress through indoor and field testing cannot be widely promoted in the development of coal-bed methane. The coal reservoir has strong structure and large heterogeneity difference[5-6], and the in-situ stress value obtained by empirical prediction method is usually not accurate enough. How to obtain the in-situ stress value under the existing conditions is an unsolved problem in the exploration and development of coal-bed methane.

Hydraulic fracturing is an important stimulation measure for oil and gas wells, and also a necessary link in the exploitation of coal-bed methane[7]. A large number of hydraulic fracturing construction data provide conditions for understanding and obtaining ground stress. Scholars at home and abroad have done a lot of research on the stress distribution around the wellbore. Professor Mark D. Zoback has given specific expressions for the stress state distribution around the wellbore and the failure mechanism of the wellbore under different well types; E. According to the maximum normal stress strength theory and the stress state around the wellbore, Professor Fergel gave the specific expression form of fracture initiation, etc[8-9].

After construction, the closure stress is generally regarded as the minimum in-situ stress[10], but this is obviously not accurate enough. First of all, the elastic modulus of coal and rock is low, belonging to soft rock stratum[11]. Long time high-pressure construction has changed the original stress state[12-13]; Secondly, the natural fractures of coal seams are developed[14], and fracturing often results in multiple fractures, complex fractures, etc. Due to the influence of geological structure and coal rock reservoir heterogeneity, the in-situ stress between adjacent wells sometimes differs greatly[15]. The in-situ stress values obtained from a single well are often unrepresentative, and the maximum in-situ stress values cannot be obtained. This paper comprehensively considers the fracturing operation data of multiple wells, such as fracture pressure, well depth data and other parameters, derives the fracture initiation model, and on this basis, reverses the display format of the maximum and minimum regional horizontal in-situ stress values, providing a new idea for the establishment of regional in-situ stress field for coal-bed methane wells.

2. Model Establishment

With reference to the wellbore stress distribution state, stress coordinate system transformation relationship and other related knowledge[16-17], the coal seam borehole coordinate system OXYZ is established, as shown in Fig. 1. In order to establish the relationship between the borehole wall stress coordinate system and the three-dimensional in-situ stress of the formation, it is not prevented to establish the 0123 coordinate system of the maximum and minimum in-situ stress and overburden pressure at a point along the shaft axis as the origin. If the azimuths α of the borehole calibrated with the maximum horizontal in-situ stress are respectively, well inclination angle β, then the two coordinate systems have the following geometric relationship: first rotate the azimuths α along the overburden pressure, and then rotate β the overburden pressure to the shaft direction.

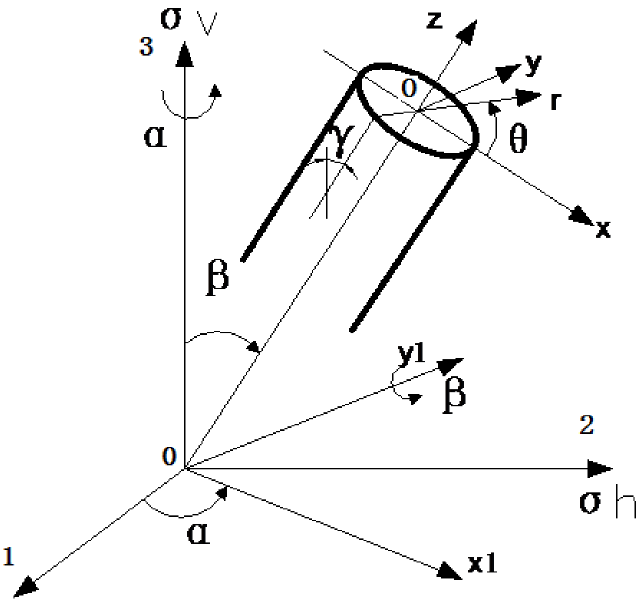

Fig.1 Coordinate system conversion diagram of borehole stress

The transformation relationship between coordinate system 0123 and coordinate system OXYZ can be obtained through the following matrix transformation:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\beta\cdot\cos\alpha & \cos\beta\cdot\sin\alpha & -\sin\beta \\ -\sin\alpha & \cos\alpha & 0 \\ \sin\beta\cdot\cos\alpha & \sin\beta\cdot\sin\alpha & \cos\beta \end{bmatrix} \times \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} \tag{1}$$

Then the relationship between the maximum horizontal in-situ stress, the minimum horizontal in-situ stress and the stress components in X and Y directions can be obtained as follows:

$$\begin{cases} \sigma_x = \left(\sigma_H \cdot \cos^2\alpha + \sigma_h \cdot \sin^2\alpha\right)\cos^2\beta + \sigma_v \cdot \sin^2\beta \\ \sigma_y = \sigma_H \cdot \sin^2\alpha + \sigma_h \cdot \cos^2\alpha \end{cases} \tag{2}$$

Where, σ_x is the stress component in X direction; σ_y is the stress component in Y direction; σ_v is the overburden pressure of rock.

According to the conversion relationship between coordinate systems, the conversion relationship between the circumferential stress under the rock column coordinate system of the shaft wall and the rectangular coordinate system is as follows:

$$\sigma_{\theta\theta} = \left(\sigma_x + \sigma_y\right) - 2\left(\sigma_x - \sigma_y\right)\cos 2\theta - 4\tau_{xy}\sin 2\theta - P_b \tag{3}$$

Where, $\sigma_{\theta\theta}$ is the circumferential stress along the shaft wall direction; τ_{xy} is the shear stress of XY plane; P_b is the bottom hole hydrostatic column pressure.

When considering the influence of pore pressure inside the reservoir and ignoring the effect of shear stress on the circumferential stress, the hydraulic fracture initiation criterion: when the maximum circumferential tensile stress is greater than the rock tensile strength, the fracture initiation criterion is as follows:

$$-\sigma_t = \sigma_{\theta\theta} - P_p \tag{4}$$

Combined with Equations (3) and (4), considering that the stress components of 0123 coordinate system in OXYZ coordinate system are obviously different under the conditions of different well inclination angles and azimuths, two forms of hydraulic fracturing wellbore fracturing equation can be obtained by sorting out, namely Kirch simplified equation is as follows:

$$\begin{cases} P_f = 3\sigma_x - \sigma_y - P_p + \sigma_t & \sigma_x < \sigma_y \\ P_f = 3\sigma_y - \sigma_x - P_p + \sigma_t & \sigma_x > \sigma_y \end{cases} \tag{5}$$

Where, P_p is reservoir pore pressure; P_f is the lowest bottom hole construction pressure for formation fracturing.

In order to obtain the relationship between fracture pressure and basic data of well bore, Bernt Sivge Aadnoy brings equation (2) into equation (5) [18-19]. The following relationship can be obtained by separating variable:

$$\begin{cases} P_f + P_p - \sigma_t - 3\sigma_v \sin^2\beta = \left(3\cos^2\alpha\cos^2\beta - \sin^2\alpha\right)\cdot\sigma_H \\ \qquad + \left(3\sin^2\alpha\cos^2\beta - \cos^2\alpha\right)\cdot\sigma_h \qquad \sigma_x < \sigma_y \\ P_f + P_p - \sigma_t + \sigma_v \sin^2\beta = \left(3\sin^2\alpha - \cos^2\alpha\cos^2\beta\right)\cdot\sigma_H \\ \qquad + \left(3\cos^2\alpha - \sin^2\alpha\cos^2\beta\right)\cdot\sigma_h \qquad \sigma_y < \sigma_x \end{cases} \tag{6}$$

By analyzing the above formulas, it can be seen that fracture fracturing, formation pore pressure, rock tensile strength, well deviation angle, azimuth angle and overburden pressure parameters can be obtained from logging and fracturing operations, and only the maximum and minimum horizontal in-situ stresses are unknown parameters. The above formula can be abbreviated as:

$$P = a\cdot\sigma_H + b\cdot\sigma_h \tag{7}$$

Obviously, the maximum and minimum in-situ stresses can be obtained from two groups of data. There is a certain error in logging and construction parameters, and there is a certain error between the calculated value and the actual value. Obviously, the construction data of the same area and layer can be increased to reduce the error value. When there are n groups of data, the overdetermined equations in the following matrix form can be obtained[20]:

$$\begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_n \end{bmatrix} = \begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \\ \vdots & \vdots \\ a_n & b_n \end{bmatrix} \cdot \begin{bmatrix} \sigma_H \\ \sigma_h \end{bmatrix}, \quad P = C\cdot X \tag{8}$$

When the number of equations is greater than the number of unknowns, it will evolve into over determined equations. There are many wells in the CBM block, and the data can easily meet the compatibility of the equations. However, the optimal solution of the stress value should minimize the error. Using the idea of least squares[21] for reference, define the variance of matrix equation:

$$e^2 = \left(P - C\cdot X\right)^T \cdot \left(P - C\cdot X\right) \tag{9}$$

According to the matrix knowledge, the derivation of the above formula X^T and X is equivalent. When the derivation of the above formula is obtained, the derivative value is 0 when the variance is at the minimum point. The results are as follows:

$$\frac{\partial e^2}{\partial X^T} = C^T C X - C^T P = 0 \tag{10}$$

Then we can get:

$$X = \left(C^T C\right)^{-1} \cdot C^T \cdot P$$

Considering the influence of depth, the stress is expressed by equivalent density in the calculation process. Considering the difference between the actual azimuth and the azimuth in this paper, the calculation process should first give the direction of the maximum or minimum horizontal in-situ stress, and combine the actual well deviation angle φ to obtain the well deviation angle α in the above formula.

It can be seen from the above model that it is impossible to judge the size of stress components σ_x, σ_y, before calculation. Therefore, two forms of equations can be obtained for each parameter. When there are n groups of data, 2^n equations with the same form can be obtained obviously, and then 2^n solutions can be obtained. The solution that can minimize the variance can be considered as the optimal solution.

3. Ground Stress Calculation of a Block in the South of Qinshui Basin

Qinshui Basin is the main area of coal-bed methane exploration and development in China. Water fracturing construction provides a lot of data for understanding and analyzing the physical properties of coal seams. In this paper, six wells in a block in the south of Shizhuang in the south of Qinshui Basin are selected as examples to calculate the horizontal in-situ stress values in this area. The target spacing of 6 coal-bed gas wells is about 300m and the burial depth is 800-900m, belonging to Shanxi Formation of Lower Permian System. The crack monitoring results show that the included angle between the maximum in-situ stress direction and the due north direction is 75 °, and the tensile strength of coal and rock is 1MPa. See Table 1 for specific parameters.

Table 1. Basic data of six wells in south Shizhuang

wwell number	Vertical depth/m	Formation pressure gradient/g/cm^3	Fracturing gradient/g/cm^3	Overburden pressure gradient/g/cm^3	well deviation/°	azimuth/°
1	870	0.68	3.71	2.10	2.34	305.50
2	917	0.70	3.22	2.10	16.00	58.60
3	948	0.69	2.98	2.10	19.40	127.40
4	890	0.68	3.64	2.10	20.00	215.00
5	821	0.67	3.61	2.10	32.00	301.00
6	828	0.68	2.96	2.10	25.70	352.00

Tabel 2. Calculate results of maximum and minimum in-situ stress

wwell number	Vertical depth/m	Maximum horizontal principal stress gradient/g/cm^3	Maximum horizontal principal stress/MPa	Minimum horizontal principal stress gradient/g/cm^3	Minimum horizontal principal stress/MPa	Measured closure stress/MPa
1	870	2.14	18.62	1.87	16.27	17.64
2	917	2.14	19.62	1.87	17.15	16.96
3	948	2.14	20.29	1.87	17.73	19.82
4	890	2.14	19.05	1.87	16.64	18.44
5	821	2.14	17.57	1.87	15.35	17.01
6	828	2.14	17.72	1.87	15.48	16.53

The maximum horizontal in-situ stress gradient is 2.14 g/cm^3, the minimum horizontal in-situ stress gradient is 1.87 g/cm^3, and the overburden pressure gradient is 2.10 g/cm^3. The calculated and measured results show that:

①The relationship between the three dimensional stress is that the minimum horizontal in-situ stress<the overburden pressure<the maximum horizontal in-situ stress, and the maximum and minimum horizontal in-situ stresses are close, with the range not exceeding 3MPa. The crack monitoring results show that the cracks in this area are mainly vertical cracks after construction, and the crack reconstruction volume is large, which is consistent with the ground stress calculation results[22];

②The measured closing pressure is slightly greater than the minimum horizontal in-situ stress and less than the maximum horizontal in-situ stress. The mean value of closing stress is 1.41MPa higher than the mean value of minimum horizontal in-situ stress, which is consistent with the theory. The closure stress is greater than the minimum horizontal in-situ stress due to multiple cracks or cracks not cracking along the maximum in-situ stress direction; At the same time, the stress value of the coal seam will be increased to a certain extent due to the long-term fracturing construction pressure. Therefore, the measured data of closed stress prove the rationality of the calculated value of horizontal in-situ stress.

4. Conclusion

① In this paper, the wellbore stress distribution state and the fracturing initiation formula of hydraulic fracturing are summarized and derived. On this basis, the overdetermined equations based on multiple sets of fracturing operation data are established, and the calculation model of horizontal in-situ stress is obtained. Finally, this model is applied to a block in the south of Shizhuang, Qinshui Basin, and the stress state of coal seam 3$^{\#}$ in this block is obtained;

② As an example of a block of coal bed methane in the south of Shizhuang, the calculation results show that the values of the three in-situ stresses in this area are close, and the minimum horizontal in-situ stress is the minimum among the three in-situ stresses. The calculated value is consistent with the fracture monitoring results in this area - the artificial fracture in this area is mainly vertical fracture;

③The measured closing stress is between the maximum and minimum horizontal in-situ stresses, and the closing stress is close to the minimum horizontal in-situ stress. The calculation results are consistent with the theory, which further proves the accuracy of the calculation results. This paper has a good guiding role in obtaining the horizontal in-situ stress value of coal reservoir and establishing the regional stress field.

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