Borehole stability in naturally fractured reservoirs during production tests

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Abstract: Based on the plane of weakness theory, a model for predicting borehole stability in fractured reservoirs under different stress states was established and the equations for solving borehole stability were developed. The minimum downhole pressures required to maintain borehole stability under different natural fracture occurrences were calculated by using the data from a well in the Tazhong (central Tarim) area, Tarim Basin, west China. Several conclusions were drawn for naturally fractured reservoirs with a dip angle from less than 10 ° to greater than 30 °. Application in three wells in the Tazhong area indicates that this model is practically useful.

Key words: Production test, fractured reservoir, borehole stability, fracture dip, azimuth of fracture

1 Introduction

Borehole stability problems during petroleum production cause substantial problems in all areas of the world (Aadnoy, 1988; Zheng, 1998). Studies of borehole stability mainly concentrated on the chemical performance of drilling fluids, and appropriate fluid systems were developed to ensure the stability of shales with different physical and chemical properties (Chen et al, 2003a; Deng and Meng, 2003). From shallow to deep drilling, from gentle continental sedimentary basin characterized by simple geological conditions to piedmont structural belts, active seismic zones and offshore structures with strong tectonic activity, stability problem is getting more serious (Aadnoy and Ong, 2003; Morita, 1995). Borehole instability during drilling is not only connected with the chemical properties, but also with the density of drilling fluids (Hale and Mody, 1992). When drilling a hole, the balance state of stresses near the borehole is broken down by the process of stress removal through drilling fluid circulation (van Oort et al, 1996). The support to the borehole wall is now provided by the hydrostatic pressure of the drilling fluid column. Significant progress has been made in the mechanics of borehole stability (Ottesen and Kwakwa, 1991). In the late 20th century, the coupled theory of chemistry and mechanics was the first step to solve the problem of shale stability (Mitchell and Goodman, 1987). So far, there is no report on the borehole stability in fractured reservoirs during production tests. Research on the borehole stability in fractured reservoirs has important engineering significance for production tests (Chen et al, 2003b).

2 Model of borehole stability in fractured reservoirs

Suppose that a fracture plane in the formation is a plane of weakness, and that the strength of the formation is identical in other directions. The criterion for failure to occur along this plane can be written in the following form (Jaeger et al, 2007):

$$\sigma_1 - \sigma_3 = \frac{2(S_w + \mu_w \sigma_3)}{(1 - \mu_w \operatorname{ctg} \beta) \sin 2\beta} \quad (1)$$

where σ_1 is the maximum principal stress; σ_3 is the minimum principal stress; S_w is the cohesion of the plane of weakness; μ_w is the coefficient of internal friction of the plane of weakness; and β is the angle between the normal to the plane of weakness and the direction of the maximum principal stress, σ_1 .

The stress difference required to cause slippage along the plane of weakness can be found from Eq. (1). If $\beta = \phi_w$ or $\beta = \frac{\pi}{2}$ (ϕ_w is the angle of internal friction of the plane), Eq. (1)

shows $\sigma_1 - \sigma_3 \rightarrow 0$, i.e. slippage will not occur; if

$$\phi_w < \beta < \frac{\pi}{2} \quad (2)$$

and the stress difference, $\sigma_1 - \sigma_3$, meets Eq. (1), slippage will occur. Otherwise, rock mass failure occurs and obeys the following relationship:

$$\sigma_1 - \sigma_3 = 2(S_0 + \mu_0 \sigma_3)[\sqrt{(\mu_0^2 + 1)} + \mu_0] \quad (3)$$

where μ_0 is the coefficient of internal friction of rock mass; S_0 is the cohesion of rock mass.

In cylindrical coordinates, the stresses acting on the

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borehole wall of a vertical well can be expressed as follows (Jin et al, 1999a; 1999b):

$$\begin{cases} \sigma_r = p - \delta\phi(p - p_p) \\ \sigma_\theta = -p + (1 - 2\cos 2\theta)\sigma_H + (1 + 2\cos 2\theta)\sigma_h \\ \quad + \delta\left[\frac{\zeta(1-2\nu)}{1-\nu} - \phi\right](p - p_p) \\ \sigma_z = \sigma_v - \nu[2(\sigma_H - \sigma_h)\cos 2\theta] + \delta\left[\frac{\zeta(1-2\nu)}{1-\nu} - \phi\right](p - p_p) \end{cases} \quad (4)$$

where σ_H is the maximum horizontal in-situ stress; σ_h is the minimum horizontal in-situ stress; σ_v is the vertical stress; p_p is the pore pressure; p is the fluid pressure; ϕ is the reservoir porosity; ζ is the coefficient of tectonic stress; ν is the Poisson ratio; θ is the angle between the maximum in-situ stress and the current orientation, anticlockwise as positive. For a permeable borehole wall, $\delta = 0$; otherwise $\delta = 1$.

Under different in-situ stress conditions or drilling fluid pressures, there are three cases for the principal stresses acting on the borehole wall:

$$\begin{aligned} \sigma_\theta &> \sigma_z > \sigma_r \\ \sigma_z &> \sigma_\theta > \sigma_r \\ \sigma_z &> \sigma_\theta > \sigma_r \end{aligned}$$

If $\sigma_\theta > \sigma_z > \sigma_r$, drilling fluid pressure required to maintain the stability of the plane of weakness can be written as follows:

$$p_{cr} = \frac{(1 - 2\cos 2\theta)\sigma_H + (1 + 2\cos 2\theta)\sigma_h - mS_w - [m\mu_w(\delta\phi - \alpha) + \delta(k_1 + \phi)]p_p}{m\mu_w(1 - \delta\phi) + 2 - \delta(\phi + k_1)} \quad (5)$$

with

$$\begin{aligned} m &= \frac{2}{(1 - \mu_w \cotg \beta) \sin 2\beta} \\ k_1 &= \delta\left[\frac{\zeta(1-2\nu)}{1-\nu} - \phi\right] \end{aligned}$$

where α is the coefficient of effective stress.

In earth coordinates (N, E, Sky), there is a theoretical relationship between TR , DIP , and $\vec{n}$.

$$\begin{aligned} \vec{n} &= i \sin(DIP) \cos(TR) + j \sin(DIP) \sin(TR) + k \cos(DIP) \\ &= ia_1 + ja_2 + ka_3 \end{aligned} \quad (6)$$

where TR and DIP are the trend (or strike) and dip of the plane of weakness; $\vec{n}$ is the normal vector of the plane of weakness.

In principal stress coordinates, the directional vector of the major principal stress is $\vec{N}_1$ and can be written as follows (Chen et al, 1995):

$$\vec{N}_1 = i \sin \theta - j \cos \theta \quad (7)$$

The directional vector of major principal stress (σ_θ) can be written as follows:

$$\begin{aligned} \vec{N} &= i[\cos(HA) \sin \theta + \sin(HA) \cos \theta] \\ &\quad + j[\sin(HA) \sin \theta - \cos(HA) \cos \theta] \end{aligned} \quad (8)$$

where HA is orientation of the maximum in-situ stress.

In earth coordinates, the angle between the normal to the plane of weakness and the major principal stress (σ_θ) is β , and therefore

$$\cos \beta = \frac{\vec{n} \cdot \vec{N}}{|\vec{n}| \cdot |\vec{N}|} \quad (9)$$

If $\sigma_z > \sigma_\theta > \sigma_r$, drilling fluid pressure required to maintain the stability of the plane of weakness can be written as follows:

$$p_{cr} = \frac{\sigma_v - 2\nu(\sigma_H - \sigma_h) \cos 2\theta - mS_w + [m\mu_w(\alpha - \delta\phi) + \delta(k_1 + \phi)]p_p}{m\mu_w(1 - \delta\phi) + 1 - \delta(\phi + k_1)} \quad (10)$$

If $\sigma_z > \sigma_r > \sigma_\theta$, drilling fluid pressure required to maintain the stability of the plane of weakness can be written as follows:

$$p_{cr} = \frac{m_2 - k_2 m_1 - mS_w - (k_1 + k_2 k_2)p_p}{k_1 k_2 - k_1 - k_2} \quad (11)$$

with

$$\begin{aligned} m_1 &= (1 - 2\cos 2\theta)\sigma_H + (1 + 2\cos 2\theta)\sigma_h \\ m_2 &= \sigma_v - \nu[2(\sigma_H - \sigma_h) \cos 2\theta] \\ k_2 &= 1 + m\mu_w \end{aligned}$$

If $S_w = 0$, the stability between stratifications completely depends on frictional force. Using Eqs. (5), (10) and (11), we can easily solve the stability problem of fractured reservoirs.

3 Influence of natural fracture occurrence on borehole stability

The following data used are from a well in Tazhong area, Tarim Basin, west China.

The maximum in-situ stress orientation	NE 75 degrees
Maximum horizontal in-situ stress grads	2.46 MPa/100m
Minimum horizontal in-situ stress grads	1.67 MPa/100m
Pore pressure grads of the formation	1.1 MPa/100m

Ignoring the effect of S_w , and with Eqs. (5), (10) and (11), we can calculate the minimum downhole pressures required to maintain borehole stability under different natural fracture occurrences.

From Fig. 1, we can draw the following conclusions.

1) For naturally fractured reservoirs having a relatively low dip angle of less than 10 degrees, a relatively low downhole pressure is required to maintain borehole stability, and the reservoir beds are relatively stable.

2) For naturally fractured reservoirs having a low dip

Fig. 1 Minimum downhole pressure required to maintain borehole stability

angle of 10-30 degrees, the minimum downhole pressure required to maintain borehole stability increases with increasing orientation (or azimuth) of natural fractures, and reaches a maximum value when the orientation of fractures is close to 80 degrees; after the orientation exceeds 80 degrees, the minimum downhole pressure required decreases with increasing orientation of natural fractures. This indicates that when the orientation of natural fractures is close to that of the maximum horizontal in-situ stress, borehole stability becomes worse; moreover, the greater the dip angle, the worse the borehole stability.

3) For naturally fractured reservoirs having a low dip angle of more than 30 degrees, the orientation of natural fractures is close to that of the maximum horizontal stress,

the borehole is stable; moreover, the greater the dip angle, the better the borehole stability.

4 Application

Acid fracturing treatment was performed in a naturally fractured carbonate reservoir in the Tazhong area. The natural fracture occurrence, collapsed interval and computational data are listed in Table 1. Table 1 illustrates that the measured pressures corresponding to borehole collapse in three wells are less than the calculated minimum downhole pressures required to maintain borehole stability. This proves that the model is applicable to predicting the minimum downhole pressure required to maintain borehole stability.

Table 1 Analysis of the collapse of reservoir beds in Tazhong area (three wells)

Well name	Natural fracture occurrence	Description of collapsed formation	Downhole pressure MPa	Minimum downhole pressure required to maintain borehole stability, MPa
TZ-X	Tensile cracks and high-angle fractures (75 degrees)	4640-4670 m. The depth of air lift with liquid nitrogen was 1500 m. Equipment for measuring well temperature was stuck at 4647.90 m. Pumping depth was 1500 m. Sand face depth was 4643.46 m.	33.0	44.5
TZ-Y	Inclined fractures were developed well, especially from 5284.02 to 5300 m, fracture density was 15 pieces/m.	5225.42-5300 m. The density of drill-in fluid (S.G.) was 1.04 g/cm ³ . Drilling returns were sharp-edged gray-white cuttings and sticking occurred frequently.	55.1	57.3
TZ-Z	Inclined fractures were developed well, especially in the lower part of the interval that production test was performed.	4633.40-4699.05 m. Sticking occurred frequently. And significant sand production.	47.0	49.2

pressure required to maintain borehole stability.

5 Conclusions

Based on the plane of weakness theory, a model was developed for predicting borehole stability in fractured reservoirs under different stress states and the following conclusions were drawn:

1) For naturally fractured reservoirs with a very low dip angle of less than 10 degrees, the minimum downhole pressure required to maintain borehole stability is relatively low.

2) For naturally fractured reservoirs with a low dip angle of 10-30 degrees, the minimum downhole pressure required to maintain borehole stability increases with increasing azimuth of natural fractures, and reaches a maximum value when the azimuth of fracture is close to 80 degrees; after the azimuth exceeds 80 degrees, the pressure required to maintain borehole stability decreases with the increasing azimuth of natural fractures. This indicates that when the azimuth of natural fractures is close to the orientation of maximum horizontal in-situ stress, borehole stability becomes worse; moreover, the greater the dip angle, the worse the borehole stability.

3) For naturally fractured reservoirs with a dip angle of greater than 30 degrees, when the azimuth of natural fractures is close to the orientation of maximum horizontal stress, borehole stability becomes better; moreover, the greater the dip angle, the better the borehole stability.

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