A prediction of breakdown pressure from damaged deviated well

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Abstract. It has been proved that formation damage is an important reason of abnormal high breakdown pressure (BP), but few quantitative prediction model considering formation damage has been established. In this paper, formation is considered as homogeneous linear elastic small deformation material, an arbitrary deviated well is taken as the research object, in-situ stress and the wellbore injection pressure in the surroundings of borehole wall are calculated on the base of elastic mechanics. Additional fracturing fluid infiltration pressure is calculated based on the empirical relationship of permeability and porosity combined with Darcy’s law of fracturing fluid in poro-elastic media. Based on the stress superposition principle as well as the tensile stress failure criterion, the breakdown pressure prediction model of deviated open hole well with damage is established for the first time, and influence of formation damage on breakdown pressure is quantitatively simulated. For a given in-situ stress regime, the results display breakdown pressure of both damaged well and undamaged well increases with the increase of deviation angle and azimuth angle, the former is always higher than the latter. Moreover, the BP and additional BP Increment is not large when deviation or azimuth angle is less than 30°. On the other hand, additional BP increment rapidly rises more when damaged permeability ratio is less than 0.135 and it can even reach 10MPa in this example.

1. Introduction

Hydraulic fracturing technology is necessary for low-permeability formation, and the breakdown pressure (BP) prediction is an extremely important parameter to ensure reasonable configuration of hydraulic fracturing equipment and optimize operation parameters [1-3]. For low-permeability formation, there is usually a high breakdown pressure [4] and it is easy to be damaged [5]. A large number of field practices and laboratory experiments [6-7] have proved that formation damage is the main cause of abnormal high breakdown pressure, which can lead to very difficulties to fracturing operation. Some tight low-permeability formation can cause abnormal BP after damaged, resulting in high hydraulic fracturing pressure or even the treatment failure. Therefore, it is of great significance to research the BP of damaged well.

Hubbert [8] first proposed the model for predicting BP based on the maximum tensile stress theory. Wan [9] summarized the early BP calculation formula for vertical open-hole wells. Yew [10] believes that pore pressure and rock tensile strength have an important influence on rock initiation, and simplified the calculation formula for breakdown pressure on the tensile strength criteria. Zhou [11] summarized the current formation BP prediction technology in detail. Although there are many
fracture criteria of formation rocks, the maximum tensile stress criterion is widely used in hydraulic fracturing [12].

Daneshy [13] took the lead in research on fracturing in deviated wells. Yu [14] put forward the stress distribution model on well wall, prediction method on BP and initiation position in base of rock tensile failure criterion. Chen [15] proposed the calculation model of BP of inclined well considering pore pressure, operation conditions and fracturing fluid seepage effect. Hossain [16] discussed the influence of wellbore track, perforation and principal stress azimuth angle under arbitrary deviation or azimuth angle on hydraulic fracture initiation and fracture extension.

Zeng [17] established a BP prediction model considering the infiltration effect by applying the maximum tension stress principle, and verified the influence rule of infiltration effect on fracture pressure of open holes. Li [18] established a model predicting BP of damage well by introducing skin pressure drop to modify the conventional calculation method. However, there is a great deviation in the calculated results. In fact, almost no quantitative prediction model of the breakdown pressure considering formation damage has been established.

2. Simulation model of breakdown pressure of deviated damaged well

During the hydraulic fracturing operation, the wellbore wall is subjected to the hydraulic pressure transmitted from fracturing fluid inside the wellbore, the stresses exerted on the wellbore by the outside in-situ stress, and additional pressure caused by the fracturing fluid leak into inside the rock because of pore pressure difference.

2.1. Stress distribution of in-situ stress on the deviated wellbore wall

Considering the wellbore radius is much larger than its radial size, the stresses of the surrounding rock can be simplified as a plane strain problem in elastic mechanics.

The initial in-situ principal stresses were described as vertical stress as \( \sigma_v \), horizontal maximum principal stress \( \sigma_H \) and minimum principal stress \( \sigma_h \). Regard the well shown in Figure 1 as an inclined well with deviation angle of \( \psi \) and an azimuth angle of \( \beta \).

\[ \begin{align*}
\sigma_x &= (\sigma_H \cos^2 \beta + \sigma_h \sin^2 \beta) \cos^2 \psi + \sigma_v \sin^2 \psi \\
\sigma_y &= \sigma_H \sin^2 \beta + \sigma_h \cos^2 \beta \\
\sigma_z &= (\sigma_H \cos^2 \beta + \sigma_h \sin^2 \beta) \sin^2 \psi + \sigma_v \cos^2 \psi \\
\tau_{xy} &= 0.5 \times (\sigma_h - \sigma_H) \sin 2\beta \cos \psi \\
\tau_{xz} &= 0.5 \times (\sigma_H \cos^2 \beta + \sigma_h \sin^2 \beta - \sigma_v) \sin 2\psi \\
\tau_{yz} &= 0.5 \times (\sigma_h - \sigma_H) \sin 2\beta \sin 2\psi
\end{align*} \]

2.2. Figure 1. Stress conversion coordinate.

Convert the in-situ stress coordinate system (H, h, v) to the corresponding coordinate system (X, Y, Z), the initial in-situ stress was translated as follows:
The stress state at the borehole wall [19] is characterized in polar coordinates as follows:

\[
\begin{align*}
\sigma_r &= p_{in} \\
\sigma_\theta &= \sigma_x + \sigma_y - 2(\sigma_x - \sigma_y) \cos \theta - 4\tau_{xz} \sin \theta \\
\sigma_z &= \sigma_x - 2\nu(\sigma_x - \sigma_y) \cos \theta - 4\nu \tau_{xz} \sin \theta \\
\tau_{r\theta} &= 0 \\
\tau_{rz} &= 0 \\
\tau_{de} &= 2(-\tau_{xz} \sin \theta + \tau_{yz} \cos \theta)
\end{align*}
\] (2)

2.2. Stress induced by injection fluid
When the fluid was injected into the wellbore, the induced stresses are expressed in cylindrical coordinates as:

\[
\begin{align*}
\sigma_r &= p_{in} \\
\sigma_\theta &= -p_{in} \\
\sigma_z &= c_p p_{in}
\end{align*}
\] (3)

2.3. Stress caused by fracturing fluid infiltration
According to Lubinski’s research [20] that fluid follows Darcy’s law in porous elastic media, the additional stress on the formation generated by fracturing fluid infiltration is:

\[
\begin{align*}
\sigma_r &= -\delta \phi p_{in} \\
\sigma_\theta &= \delta \left( \frac{\alpha (1-2\nu)}{(1-\nu)} - \phi \right) (p_{in} - p_p) \\
\sigma_z &= \delta \left( \frac{\alpha (1-2\nu)}{(1-\nu)} - \phi \right) (p_{in} - p_p)
\end{align*}
\] (4)

For damaged formations, the following empirical relationship between permeability and porosity before and after damage is obtained based on the research by Labrid [21]:

\[
\frac{k_d}{k_o} = M \left( \frac{\phi}{\phi_o} \right)^{n}
\] (5)

2.4. Superimposed total effective stress and failure criterion
Superimpose the stress components derived above on the base of linear superposition principle, the superimposed stress [14,16] on the surrounding rock of the inclined well under the combined action of in-situ stress, wellbore fluid pressure and infiltration is expressed as:

\[
\begin{align*}
\sigma_r &= p_u - \delta \phi (p_u - p_p) \\
\sigma_\theta &= -p_u + \sigma_z + 2(\sigma_x - \sigma_y) \cos \theta - 4\tau_{xz} \sin \theta - \delta \left[ \frac{\alpha (1-2\nu)}{(1-\nu)} - \phi \right] (p_u - p_p) \\
\sigma_z &= c_p p_u + \sigma_z - 2\nu(\sigma_x - \sigma_y) \cos \theta - 4\nu \tau_{xz} \sin \theta + \delta \left[ \frac{\alpha (1-2\nu)}{(1-\nu)} - \phi \right] (p_u - p_p) \\
\tau_{r\theta} &= 0 \\
\tau_{rz} &= 0 \\
\tau_{de} &= 2(-\tau_{xz} \sin \theta + \tau_{yz} \cos \theta)
\end{align*}
\] (6)
For the 3D stress field at any position on the borehole wall of an inclined well, the three principal stresses at this point can be calculated by composite stress theory [16, 19]:

\[
\begin{align*}
\sigma_1 &= \sigma_{pr} \\
\sigma_2 &= \frac{1}{2} \left[ (\sigma_{p0} + \sigma_{pz}) + \sqrt{(\sigma_{p0} - \sigma_{pz})^2 + 4\tau_{p0z}^2} \right] \\
\sigma_3 &= \frac{1}{2} \left[ (\sigma_{p0} + \sigma_{pz}) - \sqrt{(\sigma_{p0} - \sigma_{pz})^2 + 4\tau_{p0z}^2} \right]
\end{align*}
\]  

(7)

Hossain believes that however the local stress distribution determined by fracturing test data. Based on Terzaghi’s principle, considering the influence of pore fluid pressure, and combined with maximum tension principle, the breakdown pressure prediction model is obtained as follows:

\[
\sigma_3 - \eta p_p \leq -\sigma_i
\]

(8)

Obviously, the injection fluid pressure is included in eq (8), and the pressure in eq. (8) is the formation breakdown pressure of deviated damaged well. The BP is searched and obtained by dichotomy under giving in-situ stress field and well trajectory.

3. Analysis of influence of reservoir damage on fracture pressure

The horizontal maximum/minimum principal stress of a well in western China is 70MPa and 58MPa, and the vertical stress is 75MPa. Experiments show the Boit constant is 0.65, Poisson's ratio is 0.25, and porosity is 20%. Then the model established in this paper is used to simulate the breakdown pressure of an arbitrary deviated undamaged/damaged well, and the corresponding analysis is completed.

3.1. Variation law of breakdown pressure

Figure 2 shows the variation curve of the breakdown pressure of undamaged/damaged well with well deviation and azimuth, from which the following rules can be observed.

1. For vertical wells, whether the formation is damaged or not, its breakdown pressure is irrelevant to deviation and azimuth angle.
2. For deviated wells, the breakdown pressure generally increases with the increase of the deviation angle and azimuth angle, and the increase is greatly related to deviation angle and azimuth angle. The increment is relatively small compared with vertical wells when deviation and azimuth angle are less than 30°.
3. The maximum increment occurs when the inclination angle is larger than 45° and the azimuth angle is around 60°.
3.2. Influence of formation damage on breakdown pressure

The effect of different deviation and azimuth angles on breakdown pressure under the condition of different permeability ratios \( k_d/k_o \) after damage is demonstrated in Figure 3. From the simulation results, the following rules can be discovered:

1. BP increases in both vertical and deviated of wells, but the increment of vertical well is smaller. When the formation damage permeability ratio is 0.422 and 0.135, the corresponding fracture pressure increment of vertical wells increases are 1.4MPa and 2.9MPa.

2. The BP increment goes up with the increase of deviation and azimuth angle. When the deviation angle and azimuth angle are less than 30°, the BP increment is small, and the deviation and azimuth angle at which the maximum increment appears are consistent with the angle at which the maximum fracture pressure occurs.

![Figure 3. Influence of formation damage on BP increment.](image)

Figure 3. Influence of formation damage on BP increment.

Figure 4. Influence of damage permeability ratio on the BP increment.

The influence of different permeability ratio \( k_d/k_o \) after damage on BP is shown in Figure 4 (the number in the figure is the deviation angle, min and max are the minimum and maximum BP increment of the 0-90° azimuth angle at this deviation angle). It is indicated that for any deviated angle and azimuth angle, the BP increment always goes up with the increase of the permeability ratio after damage, and the increase rate is faster and faster with the increase of the permeability ratio. When the permeability ratio is less than 0.15, BP increases significantly. The BP increment induced by formation damage can reach 10MPa.

4. Conclusions

1. The formation is considered as a homogeneous linear elastic material with small deformation. Fracturing fluid infiltration pressure is calculated based on empirical relationship between permeability and porosity changes caused by formation damage combined with Darcy's law in poro-elastic media. In-situ stress and wellbore fluid injection pressure around the borehole wall based on elasticity mechanics are considered, and a prediction model of BP on deviated damage well is...
established for the first time by maximum tensile criterion. Quantitative simulation of the effect of formation damage on BP is achieved.

(2) The change tendency of BP with deviation angle and azimuth angle in undamaged/damaged well is the same. Whether the formation is damaged or not, BP of vertical wells is irrelevant with deviation and azimuth angle, and BP of damaged well is higher than that of undamaged well. BP of deviated well generally goes up with the increase of deviation and azimuth angle, and the increment is relatively small compared with that of vertical wells when deviation and azimuth angle is less than 30°. The maximum increment appears when deviation angle is larger than 45° and the azimuth angle is around 60°.

(3) Breakdown pressure increased when formation was damaged, but the BP increment of vertical well was lowest. When damage permeability ratio is 0.422 and 0.135, BP increments of vertical well are only 1.4MPa and 2.9MPa.

(4) Fracture pressure increment increases with the increase of deviation and azimuth angle. The increase of fracture pressure is relatively small when deviation and azimuth angle are less than 30°, and the deviation angle and azimuth angle at which the maximum increment appears are consistent with the angle at which the maximum BP pressure appears.

Nomenclature

- \(k_o, k_d\): Permeability of original and damaged reservoir, mD;
- \(M, n\): Empirical constant (Generally \(M=1, n=3\));
- \(p_{fw}, p_f\): Wellbore fracture pressure and formation pressure, MPa;
- \(R, r\): Wellbore radius and extreme diameter from wellbore axis, m;
- \(A\): Biot porous elasticity coefficient, dimensionless;
- \(\Delta\): Permeability coefficient, \(\delta=1\) when the formation is permeable, \(\delta=0\) when impermeable;
- \(\Phi\): Rock porosity around wellbore;
- \(\nu\): Poisson's ratio, dimensionless;
- \(\psi, \beta\): Deviation angle and azimuth angle of inclined well;
- \(\eta_p\): Pore pressure contribution coefficient;
- \(\sigma_r\): Tension strength of rock, MPa;
- \(\sigma_{xx}, \sigma_{yy}, \sigma_{zz}\): In-situ horizontal maximum, minimum principal stress and vertical principal stress, MPa;
- \(\sigma_{xy}, \sigma_{yx}, \sigma_{zx}, \sigma_{xz}\): The three principal stress in \((X, Y, Z)\) coordinate after coordinate conversion, MPa;
- \(\tau_{xy}, \tau_{xx}, \tau_{zy}\): Shear stress generated by the in-situ principal stress in each direction, MPa;
- \(\sigma_{r}, \sigma_{\theta}, \sigma_{z}\): Radial, circumferential and axial stress, MPa;
- \(\tau_{r\theta}, \tau_{rz}, \tau_{z\theta}\): Superimposed shear stress in each direction of \((X, Y, Z)\) coordinate, MPa;

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