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Effects of fluid seepage on wellbore stability of horizontal wells drilled underbalanced

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ABSTRACT

The combination of underbalanced drilling (UBD) and horizontal wells produces high efficiency. However, UBD in horizontal wells is also risky – a lack of effective support from drilling fluid may lead to wellbore instability; formation fluid that flows from formation to the wellbore applies additional stresses to rocks around the wellbore; the existing stresses from fluid seepage which are usually ignored increase the chances of wellbore collapse. So the aim of this study is to analyze the effects of fluid seepage on wellbore rocks. Based on seepage mechanics and linear elastic theory, a new analytical model that takes fluid seepage into consideration is introduced to examine wellbore circumferential stresses, and then a new wellbore collapse pressure model is derived. When fluid seepage is taken into account, collapse pressure calculated by the new model is higher and more accurate than that calculated by the conventional model, which means that we will have a narrower mud-density window during UBD process.

Analysis of wellbore circumferential stresses shows that variation trends of radial stress and tangential stress are the same whether fluid seepage is considered or not, and that the minimum radial stress and the maximum tangential stress are reached at the wellbore wall. However, values of radial stress and tangential stress are greater when fluid seepage is considered. The effects from fluid seepage intensify with the decrease of effective fluid column pressure and diminish with the increase of radial distance. Meanwhile, sensitivity analysis has found that the borehole radius is an influencing factor and that pore pressure, cohesion strength and internal friction angle have certain impact on wellbore stability in both models.

1. Introduction

As one of the sophisticated drilling technologies, UBD in horizontal wells has been widely used and developed in recent years (Cunha et al., 2001; Shatwan et al., 2011; Springer et al., 1995). This technology has the advantages of protecting the reservoir, improving output of reservoir, improving rate of penetration, avoiding mud loss and differential sticking, etc (Bennion et al., 1996; Falk and McDonald, 1995). While during UBD operations in horizontal wells, effective fluid column pressure is lower than pore pressure, or rather, the wellbore cannot be sufficiently supported to maintain wellbore stability, which is especially true for unconsolidated rocks and rocks with low strength. Owing to negative differential pressure, fluid in the formation seeps into the wellbore during UBD, with additional stresses exerted on rocks and circumferential stresses redistributed – the additional stresses applied put the wellbore into a much more unstable condition.

A number of studies have been done to reveal mechanisms of wellbore rock failures during drilling since Westergaard (1940) published one of the earliest papers concerned with stress distribution around the borehole. For wellbore instabilities, two categories are commonly described (Zeynali, 2012; Zhu and Liu, 2013): instabilities induced by the mechanical–chemical interactions between drilling fluid and wellbore rocks, and instabilities caused by mechanical factors (rock properties, redistribution of wellbore stresses, etc) – the main factors for UBD wellbore instabilities. Analytical and numerical methods have been widely used to deal with mechanical failures (Zeynali, 2012).

Keeping wellbore stability is of vital importance during drilling operations, different analytical models and numerical models have been introduced in UBD based on different drilling characteristics and working conditions. A fully coupled poroelastic model is developed for wellbore stability analysis with an emphasis on fluid flow during UBD in vertical wells (Hodge et al., 2006), in this case, the impact of fluid flow on wellbore collapse and circumferential stresses is not fully described. Coupled models of borehole instability, rock yielding, collapse, detachment, and wellbore hydraulics

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are built to predict borehole enlargement and the borehole instability, which can be used to better predict pressure loss and fluid velocity for a sidetracked well and a hypothetical horizontal well (Hawkes et al., 2002). In terms of UBD in shale, consolidation effect on time delayed borehole stability was put forward by Aminul Islam (Islam and Pål Skalle, 2009). In other words, parameters like permeability and pore fluid viscosity and porosity have certain impact on mechanical borehole instability, but this only applies to vertical wells. To evaluate the feasibility of drilling underbalanced in highly depleted sands inter-layered with normally pressured shale, Azeemuddin (Azeemuddin et al., 2006) presented a calibrated model to calculate required mud weight for different underbalanced conditions. For a depleted reservoir in which pore pressures can be very low, a finite difference method and an elastoplastic constitutive model can be applied to analyze the undrained condition and the drained condition of horizontal wells (Parra et al., 2003). Numerical models also have been used to analyze wellbore stability and near-wellbore rock stresses (Salehi et al., 2010; Zhang et al., 2012). However, wellbore stability analysis of horizontal wells using UBD hasn't been fully studied.

A fluid-solid-chemistry model (Wang et al., 2012) and a fluid-solid coupling model (Li et al., 2011) which consider fluid seepage from drilling fluid to formations have been discussed in over-balanced drilling. However, the existing wellbore stability models for UBD don't take fluid seepage into consideration. Based on the linear elastic theory, this paper incorporates stresses produced by fluid seepage in the analysis of wellbore stability during UBD operations in horizontal wells. According to Mohr–Coulomb failure criterion, a new model for calculating collapse pressure is formed. And compared with the previous model, the differences are obtained. Meanwhile, redistribution of circumferential stresses and the results of sensitive factors analysis are figured out.

2. Wellbore stability model during UBD operations in horizontal wells

During UBD operations in horizontal wells, circumferential stresses consist of two kinds of stresses: (1) those related to in-situ stresses which include three principals (vertical stress σ_v, maximum horizontal stress σ_H and minimum horizontal stress σ_h); (2) additional stresses produced by fluid seepage from formations to the wellbore. Several hypotheses are to be put forward before the analysis is done:

(1) UBD is liquid phase or gas–liquid underbalanced drilling.
(2) The stress distribution of the wellbore can be simplified as plane strain problems, with volume force and surface force overlooked.
(3) Formation rocks are fully saturated with formation fluid, and are isotropic, homogeneous, continuous and porous media.
(4) Formation fluid is single-phase and incompressible fluid; fluid seepage is a steady flux if time and temperature effect is not considered.
(5) Formation rocks are linear elastic media before they are yielded, and deformation of rocks is small.

Based on these hypotheses, analytical solutions to circumferential stresses can be obtained with a combined analysis of stresses produced by in-situ ones and additional stresses produced by fluid seepage.

2.1. Circumferential stresses produced by in-situ stresses

For horizontal wells, the stress condition is more complicated than that of vertical wells as a result of borehole deviation. So before discussing circumferential stresses produced by in-situ stresses (σ_v, σ_H, σ_h), the value and form of in-situ stresses should be transformed into wellbore coordinate. Fig. 1(a) shows the conversion of two coordinates; the Cartesian coordinate (x', y', z') represents the direction of in-situ stresses (σ_v, σ_H, σ_h), while the Cartesian coordinate (x, y, z) is the coordinate of an inclined borehole, which can be transformed into a Cylindrical coordinate(r, θ, z) for easier calculations. Fig. 1(b) shows the plane stress condition of the wellbore in an inclined borehole (Zhang, 2013).

Combined with the plane stress condition in Fig. 1(b), stress components in the Cartesian coordinate (x, y, z) can be described as six principal stresses: σ_{xx}, σ_{yy}, σ_{zz}, τ_{xy}, τ_{yz}, τ_{yz}. The six principal stresses can be expressed as follows (Fjaer et al., 2008):

$$\begin{cases} \sigma_{xx} = \sigma_H \cos^2\beta\cos^2\alpha + \sigma_h \cos^2\beta\sin^2\alpha + \sigma_v \sin^2\beta \\ \sigma_{yy} = \sigma_H \sin^2\alpha + \sigma_h \cos^2\alpha \\ \sigma_{zz} = \sigma_H \sin^2\beta\cos^2\alpha + \sigma_h \sin^2\beta\sin^2\alpha + \sigma_v \cos^2\beta \\ \tau_{xy} = -\sigma_H \cos\beta\cos\alpha\sin\alpha + \sigma_h \cos\beta\cos\alpha\sin\alpha \\ \tau_{yz} = -\sigma_H \sin\beta\cos\alpha\sin\alpha + \sigma_h \sin\beta\cos\alpha\sin\alpha \\ \tau_{zx} = \sigma_H \cos\beta\sin\beta\cos^2\alpha + \sigma_h \cos\beta\sin\beta\sin^2\alpha - \sigma_v \cos\beta\sin\beta \end{cases} \tag{1}$$

where β is the angle of inclination; α is the angle from the direction of maximum horizontal stress to the projection line of well axis into the Cartesian coordinate (x', y', z'). In this paper, we assume that the horizontal wells are drilled in the minimum stress direction in a normal faulting stress regime, which means that $\alpha = 90°$. Fig. 2 shows the linear combination of principal stresses and effective fluid column pressure in a plane of a horizontal well. In the Cylindrical coordinate (r, θ, z), with the effect of in situ stresses ($\sigma_H, \sigma_h, \sigma_v$) and effective fluid column pressure, the redistribution of circumferential stresses can be obtained by calculating the effect of six stress components in Eq. (1) on the wellbore. By linear addition, circumferential stresses produced by in situ stresses during UBD in horizontal wells can be expressed in Eq. (2).

$$\begin{cases} \sigma_r = P_i\dfrac{R^2}{r^2} + \dfrac{\sigma_v + \sigma_H}{2}\left(1 - \dfrac{R^2}{r^2}\right) + \dfrac{\sigma_v - \sigma_H}{2}\left(1 - 4\dfrac{R^2}{r^2} + 3\dfrac{R^4}{r^4}\right)\cos 2\theta - \alpha_e P_p \\ \sigma_\theta = -P_i\dfrac{R^2}{r^2} + \dfrac{\sigma_v + \sigma_H}{2}\left(1 + \dfrac{R^2}{r^2}\right) - \dfrac{\sigma_v - \sigma_H}{2}\left(1 + 3\dfrac{R^4}{r^4}\right)\cos 2\theta - \alpha_e P_p \\ \sigma_z = \sigma_h - 2\nu(\sigma_v - \sigma_H)\dfrac{R^2}{r^2}\cos 2\theta - \alpha_e P_p \\ \tau_{r\theta} = \dfrac{\sigma_H - \sigma_v}{2}\left(1 + 2\dfrac{R^2}{r^2} - 3\dfrac{R^4}{r^4}\right)\sin 2\theta \end{cases} \tag{2}$$