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Factors influencing wellbore stability during underbalanced drilling of horizontal wells – When fluid seepage is considered

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A B S T R A C T

Underbalanced drilling (UBD) of horizontal wells has been one of the efficient technologies in the exploration and development of oil and gas fields, while wellbore instability poses a problem during the whole operation process, for fluid seepage induced by the flow of formation fluid into wellbore exerts additional stresses on wellbore. However, the impact of fluid seepage has usually been ignored by conventional analysis of wellbore stability during UBD. This paper, taking the effects from fluid seepage into consideration, introduces a new collapse pressure model for UBD of horizontal wells. A comparison of the new model with the conventional one reveals that maximum equivalent collapse density (MECD) reduces with the decrease of borehole radius and that the wellbore is more stable in a slim hole during UBD of horizontal wells. And with the change of the inclination angle, MECD is higher when fluid seepage is considered under a certain relative azimuthal angle, indicating a narrower mud weight window and a more unstable wellbore; while the variation trend of MECD with the inclination angle are quite different at relative azimuthal angle = 90° and 0°. With the change of the relative azimuthal angle, MECD obtained in consideration of fluid seepage is also greater when the inclination angles is fixed, and MECD in both conditions (when fluid seepage is considered and otherwise) decreases with the increase of the relative azimuthal angle; meanwhile, the value of θ where MECD is obtained is also analyzed.

1. Introduction

Wellbore instability has remained one of common problems in the exploration of oil and gas, which amounts to huge expenses during oil and gas drilling. Therefore, maintaining a stable wellbore is of great significance in the drilling and production of oil and gas wells. Since underbalanced drilling (UBD) is capable of improving rate of penetration and minimizing formation damage, horizontal wells is one of the technologies which can enhance well productivity, combination of these two technologies has been widely practiced, which has been proved to be highly efficient. During UBD of horizontal wells, effective fluid column pressure is lower than the formation pressure, this increases the chances of wellbore collapse, and influencing factors like well structure and well trajectory also affect wellbore stability.

Researches on wellbore stability have been conducted from various perspectives. For overbalanced drilling, types of formation rocks and drilling fluid have certain impact on wellbore stability. Chen et al. (2003) presented coupled numerical analyses to investigate the influence of fractures in the rock and Zhang et al. (2003) used dual-porosity poroelastic theory to solve the problem of horizontal well stability. Zeynali (2012) summed up types of wellbore instability from the mechanical and physico-chemical aspect during overbalanced drilling operations; and he concluded that properties of drilling mud and its interaction with the formation would affect the mechanical properties of the formation rocks and the stresses around the wellbore, especially for shale (van Oort, 2003). However, mechanical factors are the main factors that affect the stability of wellbore during UBD operations. When analyzing the effect of well structure and well trajectory on wellbore stability in overbalanced drilling, Zhang et al. (2010) and Manshad et al. (2014) used different rock strength criteria to assess wellbore stability of vertical, deviated and horizontal boreholes. And based on the results of wellbore stability analysis, Zare-Reisabadi et al. (2012) defined the optimal well trajectory during drilling and production in different in-situ stress regimes.

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Meanwhile, Kadyrov and Tutuncu (2012) incorporated borehole stability, lost circulation, hole cleaning and differential sticking for well trajectory optimization, after which recommendations for field development had been made to reduce non-productive time during drilling operations. Dutta and Farouk (2008) used a proper mechanical earth model from a nearby offset well to study wellbore failure based on well trajectory sensitivity analysis, which helped safe drilling of a horizontal well. However, there are a few studies about the influence of well trajectory and well structure on wellbore stability during UBD.

To keep wellbore stable during UBD operations, different models have been established. Salehi et al. (2007) used an elasto-plastic model combined with a finite-explicit code to estimate optimum equivalent circulating density where UBD is applied. Mclellan and Hawkes (2001) developed a software called STAB-View™ to determine the optimal range of bottom hole pressure for UBD operations and to guide UBD operations in sandstone reservoirs. Moos et al. (2003) held that rocks had scale dependent strengths and he developed a model to predict regions where compressive shear failure would occur and anticipate spalling areas. Qiu et al. (2007) presented a practical wellbore stability technique to evaluate UBD in a horizontal well in depleted reservoir; and they conducted trajectory sensitivity analysis to design preferred borehole trajectories by which wellbore instability can be minimized, but in which effects of fluid seepage wasn't fully described. Meanwhile, thermal effect on rock failure in gas-drilling was also studied (Li et al., 2014). However, models analyzing the influence of well structure and well trajectory on wellbore stability when considering fluid seepage in UBD haven't been fully studied.

This paper, by incorporating circumferential stresses produced by in-situ stress and additional stresses induced by fluid seepage, a new collapse pressure model for UBD of horizontal wells is introduced using Mohr–Coulomb criterion. Meanwhile, by comparing it with the conventional model in which fluid seepage is ignored, the impact of well structure and well trajectory (inclination angle and relative azimuthal angle) on wellbore stability during UBD of horizontal wells is put forward.

2. Analysis of circumferential stresses during UBD of horizontal wells

Before analyzing wellbore stability during UBD operations in horizontal wells, the stress state of wellbore should be known. During UBD operations in horizontal wells, stresses around the wellbore fall into two categories: in-situ stresses and the additional stresses produced by the flow of formation fluid into wellbore. It is assumed that UBD is liquid phase or gas–liquid underbalanced drilling, that formation rocks are fully saturated with formation fluid, and are isotropic, homogeneous, continuous and porous media, that formation fluid is single-phase and incompressible fluid and that fluid seepage is a steady flux without effects of time and temperature considered.

2.1. Circumferential stresses produced by in-situ stresses

In the whole drilling operation, three kinds of in-situ stresses act on the wellbore, namely, vertical stress (σ_v), maximum horizontal stress (σ_H) and minimum horizontal stress (σ_h). And during the drilling process of a horizontal well, as the angle of the well changes from vertical to deviated and to horizontal finally, stress state also changes. So before analyzing the circumferential stresses produced by in-situ stresses, coordinate systems of the wellbore should be set up. As Fig. 1(a) shows, rectangular coordinate (x', y', z') is the coordinate of in-situ stress, while ox', oy', oz' correspond to the directions of maximum horizontal stress (σ_H), minimum horizontal stress (σ_h) and vertical stress (σ_v) respectively; and rectangular coordinate (x, y, z) is the coordinate of the wellbore, where oz corresponds to the axis of wellbore, and ox and oy are in the plane perpendicular to wellbore axis.

A study of the relationship between rectangular coordinate (x', y', z') and rectangular coordinate (x, y, z) yields six stress components (σ_{xx}, σ_{yy}, σ_{zz}, τ_{xy}, τ_{yz}, τ_{yz}) in the coordinate of wellbore (x, y, z) as Eq. (1) illustrates, where i is inclination angle, °; α is relative azimuthal angle which is the angle from the direction of maximum horizontal stress to the projection line of well axis into the rectangular coordinate (x', y', z'), ° (Fjaer et al., 2008).

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

Fig. 1(b) indicates the plane stress condition of a deviated wellbore in the rectangular coordinate (x, y, z). And on the basis of Fig. 1(b), cylindrical coordinate (r, θ, z) is established for an easier calculation of wellbore stresses. And Fig. 1(c) shows the stress condition of the rock infinitesimal in the polar coordinate. Then

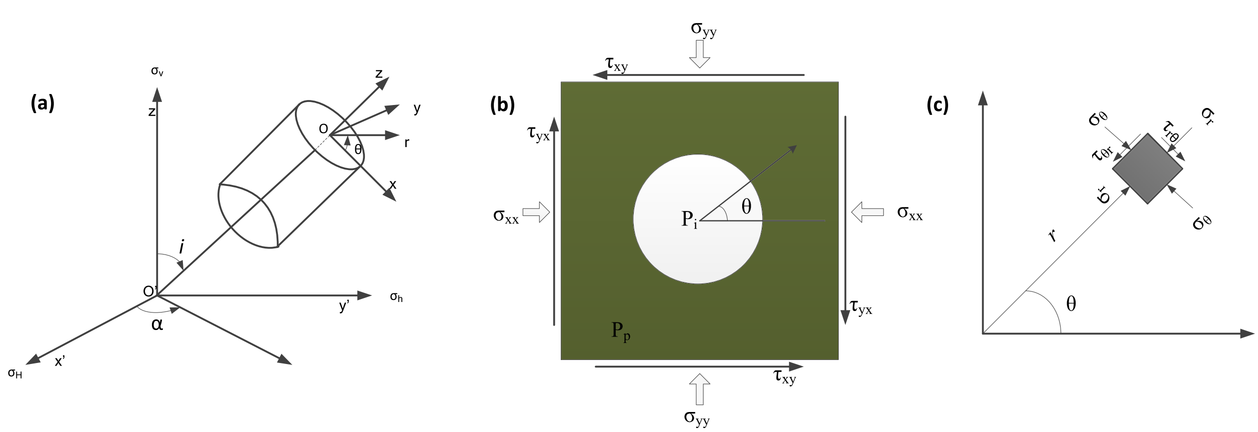

Fig. 1. (a) Coordinate system of a deviated wellbore and in-situ stresses; (b) the plane stress state of a deviated wellbore; (c) the stress state of the rock infinitesimal in the polar coordinate.