Journal of Natural Gas Science and Engineering 27 (2015) 1050–1062

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

A model for analysis of wellbore stability considering the effects of weak bedding planes

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A R T I C L E I N F O

Article history:
Received 22 July 2015
Received in revised form
28 August 2015
Accepted 22 September 2015
Available online 30 September 2015

Keywords:
Wellbore stability
Weak bedding planes
Equivalent collapse density
Influencing factors
In-situ stresses

A B S T R A C T

In conventional analysis of wellbore stability, rock is usually assumed to be isotropic, but errors occur when isotropic theory is used if there are weak bedding planes that represent the properties of rock anisotropy. Therefore, in this paper, based on circumferential stresses and a new analysis of geometrical relationships of weak bedding planes and wellbore, a new wellbore stability model that considers the effects of weak bedding planes is introduced; then, a comparison is made by comparing the new model with the intrinsic rock failure model based on actual field data, which reveals that wellbore is less stable when weak bedding planes are considered, that the wellbore of cross-dip wells is less stable than that of up-dip wells and down-dip wells in the strike-slip stress regime and that wellbore quality is better in up-dip wells. Furthermore, results show that dip angles and dip directions of weak bedding planes have significant effects on wellbore stability for different inclination angles and wellbore azimuths. Regarding the effects of in-situ stress regimes, it is found that the wellbore of down-dip wells is overall more stable and that the maximum equivalent collapse density (MECD) of wells drilled along the wellbore azimuth $\theta_{IA} = 270{-}300^{\circ}$ is relatively smaller in the normal fault stress regime; also, in the reverse fault stress regime, the MECD of both up-dip wells and wells drilled along $\theta_{IA} = 90{-}150^{\circ}$ is relatively small. Finally, the influence of the anisotropic coefficient of horizontal stresses is also analyzed.

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1. Introduction

Wellbore instability is a constant problem during the drilling of oil and gas wells and leads to large expenses. Hence, a stable wellbore is vital for the exploration and development of oil and gas. Because strength parameters are the same in all directions of isotropic rocks (Bradley, 1979), errors may result from using isotropic theory if the rock is anisotropic; for example, weak bedding planes may affect the properties of rocks and wellbore stability (Jaeger et al., 2007). Therefore, analysis of wellbore stability considering weak bedding planes is important for well drilling in formations with weak bedding planes; moreover, factors such as the parameters of weak bedding plane and in-situ stresses can also affect wellbore stability.

Research on wellbore stability was first conducted based on the assumption of linear elastic, isotropic rock (Bradley, 1979), during which anisotropic properties of rocks were left out. Then, related experiments were performed for anisotropic rocks considering weak bedding planes, and it was found that bedding plane orientations influenced both the elastic constants and yield strengths of rock (Chenevert and Gatlin, 1965) and that failure of transversely isotropic rock could be classified into sliding failure and non-sliding failure along the discontinuities (Tien et al., 2006). Moreover, Dokhani et al. (Dokhani et al., 2013) designed an experiment and presented a new model to study the effect of bedding plane orientation on pore pressure, which indicated that the distribution of pore pressure was highly affected by weak bedding planes.

Hence, based on the effects of the anisotropy of rock, Aadnoy (Aadnoy, 1988) developed an anisotropic stress model that considered anisotropic elastic properties, directional shear and directional tensile strengths; he found that neglecting the anisotropic effects introduced errors regarding tensile failure and shear failure of wellbore. Ong and Roegiers (Ong and Roegiers, 1993) introduced a model consisting of a three-dimensional analysis of

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http://dx.doi.org/10.1016/j.jngse.2015.09.053
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stress concentrations combining internal wellbore pressurization, flow and thermally induced stresses; it revealed that an inclined borehole was influenced by rock anisotropy, in-situ stress differentials and thermal conditions. With regard to the "plane of weakness" theory, Okland and Cook (Okland and Cook, 1998) discovered that wellbore instability worsened when a well was drilled parallel or very nearly parallel to bedding planes in the Oseberg field of the North Sea. The relative magnitude of the two normal stresses and the angle between a wellbore and a weak bedding plane are two conditions that determine whether the rock fails along the weak bedding plane (Aadnoy et al., 2009). Jin et al. (Jin et al., 2011) applied the "plane of weakness" theory to analyze wellbore stability in a fractured formation during a well test. In shale formation, weak bedding planes can be very unfavorable to wellbore stability, and severe stuck-pipe problems may occur as a result of failure on weak bedding planes (Wu and Tan, 2010). Therefore, based on numerical and laboratory analysis, McLellan and Cormier (McLellan and Cormier, 1996) found that wellbore instability in shale with weak bedding planes was a result of a complex interaction among bedding planes, in situ stresses, natural fractures, well trajectory, rock properties and other factors. Li et al. (Li et al., 2012) established a wellbore stability model in a shale gas well by combining logging data, real-time drilling data and in-site stress tests (tests of weak bedding planes and microstructures), the results of which were helpful for well drilling and completion design.

Many other factors can also affect wellbore stability when weak bedding planes are considered. The attack angle (the angle between the wellbore and the weak bedding plane) is a factor that affects the selection of the best trajectory for the well drilled through weak bedding planes to avoid shear and slip failures (Fekete et al., 2014; Bassey et al., 2013). Lu et al. (Lu et al., 2013) analyzed the influence of porous flow on wellbore stability considering weak bedding planes and showed that porous flow made the wellbore less stable. Ma and Chen (Ma and Chen, 2015) found that water content in shale also influenced the strength of weak bedding planes and that increased water content made the wellbore less stable. Furthermore, the design of well trajectories is also vital for a stable wellbore (Last and McLean, 1996).

In this paper, a new wellbore stability model considering weak bedding planes is introduced in which geometrical relationships of weak bedding planes and wellbore are fully analyzed in a new way, and a new solution of β is put forward (β is defined as the angle between the normal direction of a weak bedding plane and the direction of maximum principal stress). Based on a case with actual field data, a comparative analysis is presented between the new model and the intrinsic rock failure model. The effects of weak bedding plane parameters and in-situ stresses on wellbore stability are also fully analyzed.

2. Modeling

Before conducting the wellbore stability analysis, the following assumptions were made: (1) formation rock is heterogeneous and anisotropic; (2) a set of parallel weak bedding planes exists in which the strengths are low, but the strength of the rock in other directions is uniform; and (3) deformation of rock is low and linear.

2.1. Analysis of circumferential stresses

Circumferential stresses of wellbore are to be analyzed first when analyzing wellbore stability. It is known that there are three in-situ stresses acting on wellbore: maximum horizontal stress (σ_H), minimum horizontal stress (σ_h) and burden pressure (σ_v). In the drilling process, the state of the wellbore changes from a vertical section to a deviated section and finally to a horizontal section (in this paper, a horizontal well is taken as an example), along with which inclination angles and wellbore azimuths also vary. Hence, during the analysis of circumferential stresses, all types of coordinate systems should be set up and transformed, as seen in Fig. 1(a). In Fig. 1(a), (N, E, Z) is an earth-rectangular coordinate system in which ON, OE, OZ represent the direction of north, the direction of east and vertical direction of the NOE plane, respectively; in (N, E, Z), the azimuth of maximum horizontal stress θ_H is defined as the angle from the direction of north to the direction of maximum horizontal stress. Moreover, (X_1, Y_1, Z_1) is established as the in-situ stress rectangular coordinate system in which OX_1, OY_1 and OZ_1 are the directions of σ_H, σ_h and σ_v, respectively. Then, in accordance with the right hand rule, OZ_1 and OY_1 are rotated by α and i, after which wellbore rectangular coordinate system (x, y, z) is obtained. Wellbore azimuth θ_{IA} is defined as the angle between the projection line of the wellbore axis onto OX_1Y_1 and the direction of north (ON). Therefore, based on Euler's transformation and the matrix of angular transformation in Eq. (1), stress components induced by in-situ stresses in (x, y, z) are expressed in Eq. (2) (Fjaer et al., 2008).

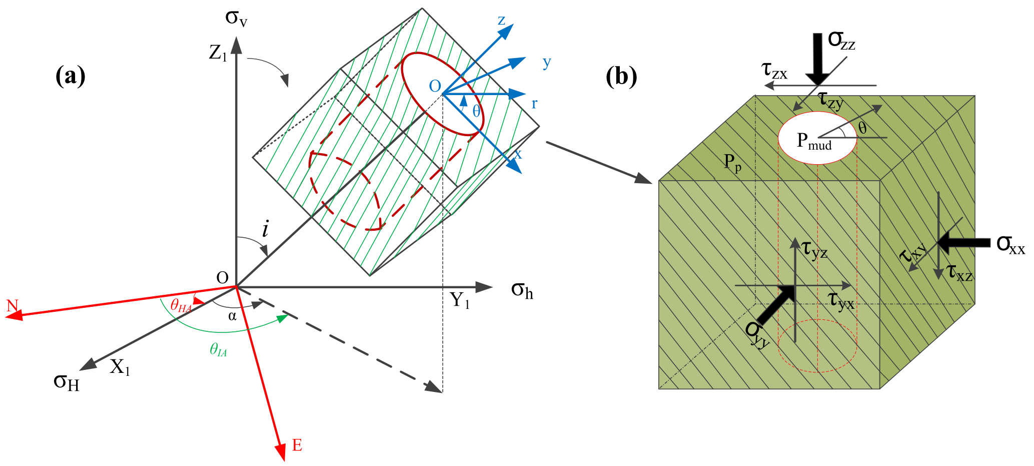

Fig. 1. (a) Coordinate systems of a deviated wellbore considering weak bedding planes and transformation of coordinates; (b) Three-dimensional stress state of rock infinitesimal in a deviated wellbore.

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