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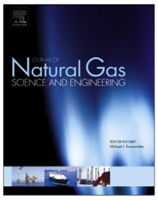

A novel model for wellbore stability analysis during reservoir depletion

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ABSTRACT

It is not common to build a geomechanical model for depleted reservoirs as logging and coring are costly and time consuming in such reservoirs. On the other hand, in regular analysis of wellbore stability, the effect of time is completely ignored. As a result, with time there will be some errors in the evaluation of wellbore stability in depleted reservoirs. In order to determine the optimum wellbore trajectory during the reservoir life, it is necessary to have a model which can estimate the rock properties based on the first full logging suite and also consider the depletion effect. In this study, a novel model is proposed which combines a mechanical earth model, borehole circumferential stresses, Mogi-Coulomb failure criteria and simulation of pore pressure variation near wellbore to determine the optimum well trajectory during drilling and production in a condensate offshore reservoir. As a main output from the application of the new model, it was found that the most stable wellbore trajectory changed after 18–27 years of production. This critical output from this study raises the need to consider the possibility of changing the designed well trajectory over the life of the reservoir to maintain wellbore stability and optimize the drilling and production operations.

1. Introduction

In recent years, wellbore stability related problems have become more significant due to the increase of drilling more complex well trajectories. After drilling a well, the rocks surrounding the well must bear the stress load that was formerly supported by the removed rocks (Al-Ajmi and Zimmerman, 2009; Fjaer et al., 2008). Redistribution of stresses around wellbore and the generation of locations with high stress concentrations are the consequences that govern borehole instability. Each rock is naturally under stresses: vertical stress due to the overburden exerted by the overlaying formations, and horizontal stresses as a result of tectonic movements (Amadei, 1984). In addition to the *in situ* stresses, the formation pore pressure, the mud pressure and the geomechanical rock properties are other effective parameters on borehole stability. To conduct borehole stability analysis, a proper shear failure criterion in conjunction with the azimuth and inclination of the well are required. In such a study, the most stable wellbore trajectory has been found to be governed mainly by the magnitude of the *in situ* stresses (Al-Ajmi and Zimmerman, 2009; Zare-Reisabadi et al., 2012).

During the production from wells, reaching an optimum fixed flow rate is essential to have the maximum recovery. However, in order to overcome the formation damage problems, an increase in the drawdown pressure might be necessary. If the raise in such drawdown results in stresses that exceed the stress resistance threshold of the rock, sand production onset will be potentially faced (Paslay and Cheatham, 1963). As a result, obtaining an optimum well trajectory for the entire life of the well is necessary to reduce the costs of operations.

The assumed rock formation behavior is a significant factor in modeling the stresses around a borehole. In this regard, Mclean and Addis (1990) pointed out that a poro-elasto-plastic model can give more realistic results than a linear elastic model. In addition, Bradford and Cook (1994) suggested using an elasto-plastic model for stress modeling and they have applied their recommendation in wellbore stability analysis for vertical well with isotropic *in situ* stresses. Furthermore, Sanfilippo et al. (1995) modeled the stresses around a borehole using an elasto-plastic model for an infinite reservoir boundary that considered a uniform drainage area for the well. Chemo-poro-elastic model is used to determine the stresses around the wellbore in shale formations (Ma et al.,). Moreover,

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Table 1
Properties of production gas.

Depth (m)	Total Gas (%)	Chromatographic breakdown ppm					
		C1	C2	C3	iC4	nC4	C5
3822	0.466	186	170	169	163	124	58
3871	0.430	85	89	169	134	175	458
3912	0.554	56	137	118	165	175	699

Risnes et al. (1982) studied the sand stresses around the borehole using poro-elastic and poro-plastic models. In their study, the wellbore was assumed to be under steady state conditions with incompressible fluid in an isotropic field stress. Their founding showed that permeability has a pivotal role in stability criterion and that a plastic area around the wellbore may occur. Also, they have concluded that as the rock becomes more consolidated, the radius of the plastic zone decreases.

Nevertheless, the basic linear elasticity modeling for the stresses around a borehole is the commonly applied assumption in the oil and gas industry worldwide. This is due to the fact that estimating the parameters that represent the plastic deformation is generally limited in practice (Mclean and Addis, 1990; Yi et al., 2004). Recently, for instance, Zare-Reisabadi et al. (2012) used a three dimensional analytical model based on linear elasticity for the determination of the optimum trajectory of well during drilling and completion. Furthermore, Dokhani et al. (2016) have utilized a three dimensional elastic model in order to study the wellbore stability during drilling. Moreover, Shiming et al. (2014) introduced a new wellbore pressure collapse model which considers the influence of fluid seepage on wellbore circumferential stresses using a linear elastic model.

On the other hand, in the literature, when wellbore stability modeling was improved by considering the poro-elasticity of the formations, the applied stability models were generally neglecting the impact of depletion on pore pressure and *in situ* stresses. For example, Dokhani et al. (2016) used a model which takes the fluid instability and strength anisotropy into consideration in order to analyze wellbore stability in shale formations. Also, Ma and Chen (2015) introduced a mathematical model which considers the stresses induced by mechanical, hydraulic and chemical effects in shale gas reservoirs. An analytical model is also proposed by Ma et al. to determine the collapse pressure which considers mechanical and chemical effects around the wellbore. However, none of these studies have paid attention to the effect of production time on wellbore stability.

Some studies on wellbore stability analysis are performed by adopting numerical methods. As an example, Mclean and Addis (1990) modeled wellbore instability numerically and pointed out that the finite element method is more accurate for predicting the behavior of stresses around the hole in comparison with linear elastic models. However, numerical methods have not become a common practice in the industry as they are time consuming and require much effort.

The purpose of this study is to model the optimal wellbore trajectory based on poro-elasticity theory where the depletion effects are considered. In order to achieve this goal, we utilized the mechanical earth model (MEM) outputs to obtain the values of *in situ* stresses and rock mechanical parameters such as Poisson's Ratio. After that, the stresses at the borehole wall are calculated and introduced to Mogi-Coulomb law to examine the potential occurrence of a shear failure. The reservoir depletion is taken into account through the usage of Hooke's law. The new model was applied to a gas condensate reservoir for which the pore pressure changes were simulated for 30 years of production. Using the proposed model, the optimum trajectory at three depths was determined for every year of production, in order to analyze the effect of depletion on wellbore stability.

2. Methodology

2.1. Determination of optimized well trajectory

First of all, to examine if the conditions of borehole collapse are fulfilled or not, comparison of the circumferential stresses around the borehole with a proper failure criterion is required. We have assumed that rocks are brittle and elastic. The *in situ* stresses in Cartesian coordinates can be obtained as a function of wellbore direction and virgin formation stresses, and they are given by Fjaer et al. (2008)

$$\sigma_x = \left(\sigma_H \cos^2 \alpha + \sigma_h \sin^2 \alpha\right)\cos^2 i + \sigma_v \sin^2 i, \tag{1}$$

$$\sigma_y = \left(\sigma_H \sin^2 \alpha + \sigma_h \cos^2 \alpha\right)\cos^2 i, \tag{2}$$

$$\sigma_{z(car)} = \left(\sigma_H \cos^2 \alpha + \sigma_h \sin^2 \alpha\right)\sin^2 i + \sigma_v \cos^2 i, \tag{3}$$

$$\tau_{xy} = 0.5(\sigma_h - \sigma_H)\sin 2\alpha \cos i, \tag{4}$$

$$\tau_{xz} = 0.5\left(\sigma_H \cos^2 \alpha + \sigma_h \sin^2 \alpha - \sigma_v\right)\sin 2i, \tag{5}$$

$$\tau_{yz} = 0.5(\sigma_h - \sigma_H)\sin 2\alpha \sin i. \tag{6}$$

In Eqs. (1)–(6), i is the well inclination, α is the azimuth angle of the well with respect to the maximum horizontal stress (σ_H) direction, σ_h is the minimum *in situ* stress, and σ_v is the vertical stress. Based on linear elasticity theory, the maximum concentration of stresses occurs at the borehole wall. The evaluation of stresses around the wellbore is also affected by rock mechanical properties, pore pressure and borehole pressure. The stresses at borehole wall in cylindrical coordinates when the borehole pressure is greater than the pore pressure (i.e., during drilling) can be expressed by

$$\sigma_r = P_w, \tag{7}$$

$$\sigma_\theta = (\sigma_x + \sigma_y) - 2(\sigma_x - \sigma_y)\cos 2\theta - 4\tau_{xy}\sin 2\theta - P_w, \tag{8}$$

Table 2
Geomechanical parameters of the studied reservoir.

Depth (m)	Minimum horizontal stress (psi)	Maximum horizontal stress (psi)	Vertical stress (psi)	Pore pressure (psi)	Poisson's ratio	Biot's coef.	Internal friction angle (deg._	Stress path
3820	9237.9	13569.6	12975.7	7061.7	0.304	0.8	35.53	0.449
3937	9509.4	14152.8	13436.2	7147.4	0.306	0.8	39.54	0.445
4060	9797.2	14771.7	13914.8	7236.4	0.315	0.8	34.05	0.430