Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 900–911

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Determination of safe mud window considering time-dependent variations of temperature and pore pressure: Analytical and numerical approaches

Alireza Gholilou[a], Pouria Behnoud far[b,*], Stephanie Vialle[a], Mahyar Madadi[a]

[a] Western Australian School of Mines, Curtin University, Perth, Australia
[b] Department of Petroleum Engineering, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 8 December 2016
Received in revised form
18 February 2017
Accepted 23 February 2017
Available online 18 July 2017

Keywords:
Mud window
Thermo-poroelastic theory
Time-dependence
Fourier series
Induced stresses

ABSTRACT

Wellbore stability is a key to have a successful drilling operation. Induced stresses are the main factors affecting wellbore instability and associated problems in drilling operations. These stresses are significantly impacted by pore pressure variation and thermal stresses in the field. In order to address wellbore instability problems, it is important to investigate the mechanisms of rock–fluid interaction with respect to thermal and mechanical aspects. In order to understand the induced stresses, different mathematical models have been developed. In this study, the field equations governing the problem have been derived based on the thermo-poroelastic theory and solved analytically in Laplace domain. The results are transferred to time domain using Fourier inverse method. Finite difference method is also utilized to validate the results. Pore pressure and temperature distributions around the wellbore have been focused and simulated. Next, induced radial and tangential stresses for different cases of cooling and heating of formation are compared. In addition, the differences between thermo-poroelastic and poroelastic models in situation of permeable and impermeable wellbores are described. It is observed that cooling and pore pressure distribution reinforce the induced radial stress. Whereas cooling can be a tool to control and reduce tangential stress induced due to invasion of drilling fluid. In the next step, safe mud window is obtained using Mohr-Coulomb, Mogi-Coulomb, and modified Lade failure criteria for different inclinations. Temperature and pore pressure distributions do not change the minimum allowable wellbore pressure significantly. However, upper limit of mud window is sensitive to induced stresses and it seems vital to consider changes in temperature and pore pressure to avoid any failures. The widest and narrowest mud windows are proposed by modified Lade and Mohr-Coulomb failure criteria, respectively.
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1. Introduction

Wellbore stability is an important issue in drilling. The formations around wellbore experience new stress conditions due to the removal of drilled rocks (Fjaer et al., 2008; Al-Ajmi and Zimmerman, 2009). Any point below ground surface carries different stresses, i.e. vertical stress due to the overburden or weight of overlaying formations, and horizontal stresses from tectonic movements and pore pressures (Amadei, 1984). Redistribution of stresses around wellbore gets balanced with mud pressure considering rock mechanical properties and geometric characteristics of a wellbore. Stresses around the wellbore are examined with failure criterion to obtain a safe mud window. Low mud weight induces shear failures while high mud weight brings about tensile failures.

Estimation of induced stresses is dependent on porous rock characteristics in conjunction with the azimuth and inclination of the drilling (Al-Ajmi and Zimmerman, 2009; Zare-Reisabadi et al., 2012). Using elasticity theory for regions with high stress concentration and checking their different failure conditions are the most conventional stability analysis method. However, Mclean and Addis (1990) suggested that a more precise result can be obtained using poro-elastoplastic model rather than a linear elastic model. Bradford and Cook (1994) used an elastoplastic model to determine stresses around a wellbore. Similarly, Sanfilippo et al. (1995)

* Corresponding author.
E-mail addresses: p.behnoud@aut.ac.it, p.behnoud@gmail.com (P. Behnoud far).
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2017.02.002
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modeled the stresses around a borehole using an elastoplastic model but for an infinite reservoir boundary. Risnes et al. (1982) studied the stresses around a borehole within sandstone formations using poroelastic models in steady state condition and assuming isotropic field stress. It is suggested that considering poroelastic model rather than pure elastic may vary the minimum and maximum limits of mud window about 12.5% and 25%, respectively (Shahabadi et al., 2006).

Although linear elasticity modeling has been used for different studies, it does not consider porous media effects (Mclean and Addis, 1990; Yi et al., 2004; Behnoud far et al., 2016). Poroelastic concept recognizes pore pressure and its diffusion effects to evolve more realistic understandings regarding various stresses or failure conditions. It was developed by Biot (1955) including Hook's elastic rules along with Darcy's law to represent pore pressure diffusion effects. Multiple solutions are proposed for diffusion equation in simple geometric condition. Typically, coupled equations have been solved using a semi-analytical solution for a vertical borehole in non-hydrostatic condition (Detournay and Cheng, 1988).

Another factor affecting wellbore stability is thermal stress effect emerged from temperature difference existing between mud and formation. This effect can be simulated simply by assuming conduction condition and ignoring fluid exchange between mud and formation. In an advanced thermal analysis, both of conduction and convection conditions can be considered. Thus, estimation of induced stress will need more complex solution by means of advanced analytical methods or numerical methods. Thermo-poroelastic model has been developed and solved numerically by Shahabadi et al. (2006).

The aim of this article is to advance and verify Shahabadi et al. (2006)'s work by utilizing a new analytical solution for the thermo-poroelastic model. This model is nearly comprehensive and considers conduction effects. Hence, this model provides an important opportunity for verifying different factors effectively on mud weight design. The analytical method proposed here employs Fourier's Laplace transform method. This solution takes advantageous of including different failure criteria, which can directly influence the safe mud window (Maleki et al., 2014). Therefore, this attempt considers thermo-poroelasticity effects as well as some different failure criteria and trajectories for wellbore stability studies.

The stresses around the wellbore are estimated. The induced stresses are also determined using a novel approach. In the next step, stresses are applied to a failure criterion and mud weights are calculated for different trajectories.

2. Analytical solutions

2.1. Stresses around the wellbore

As noted earlier, stresses can be obtained basically by assuming linearly elastic material in isotropic condition. In cylindrical coordinate system, the stresses would be the functions of radial distance and rotation angle according to well-known Kirsch equations (Aadnoy and Chenevert, 1987; Li and Purdy, 2010):

$$\sigma_{rr}=\frac{\sigma_x+\sigma_y}{2}\left(1-\frac{R^2}{r^2}\right)+\frac{\sigma_x-\sigma_y}{2}\left(1-4\frac{R^2}{r^2}+3\frac{R^4}{r^4}\right)\cos(2\theta)+\tau_{xy}\left(1-4\frac{R^2}{r^2}+3\frac{R^4}{r^4}\right)\sin(2\theta)+P_{\mathrm{w}}\frac{R^2}{r^2} \tag{1}$$

$$\sigma_{\theta\theta}=\frac{\sigma_x+\sigma_y}{2}\left(1+\frac{R^2}{r^2}\right)+\frac{\sigma_x-\sigma_y}{2}\left(1+3\frac{R^4}{r^4}\right)\cos(2\theta)-\tau_{xy}\left(1+3\frac{R^4}{r^4}\right)\sin(2\theta)-P_{\mathrm{w}}\frac{R^2}{r^2} \tag{2}$$

$$\sigma_{zz}=\sigma_z-\frac{2\nu(\sigma_x-\sigma_y)R^2}{r^2}\cos(2\theta)-\frac{4\nu\tau_{xy}R^2}{r^2}\sin(2\theta) \tag{3}$$

where σ is the normal stress, τ is the shear stress, θ is the angle measured from the azimuth of the largest horizontal stress, ν is the Poisson's ratio, P_{w} is the bottom-hole pressure, R is the wellbore radius, and r is the distance from wellbore.

2.2. Induced stresses

In advanced stage, stresses induced by distinct temperatures and fluid pressure dissipations are taken into account to speculate all effective parameters. These induced stresses can be determined through applying fluid mass balance equation and energy conservation law as elucidated by Shahabadi et al. (2006):

$$\sigma_{rr}=\frac{\alpha(1-2\nu)}{1-\nu}\frac{1}{r^2}\int_{r_{\mathrm{w}}}^{r}P^{\mathrm{f}}(r,\ t)r\mathrm{d}r+\frac{E\alpha_{\mathrm{m}}}{3(1-\nu)}\frac{1}{r^2}\int_{r_{\mathrm{w}}}^{r}T^{\mathrm{f}}(r,\ t)r\mathrm{d}r \tag{4}$$

$$\sigma_{\theta\theta}=-\frac{\alpha(1-2\nu)}{1-\nu}\left[\frac{1}{r^2}\int_{r_{\mathrm{w}}}^{r}P^{\mathrm{f}}(r,\ t)r\mathrm{d}r-P^{\mathrm{f}}(r,\ t)\right]-\frac{E\alpha_{\mathrm{m}}}{3(1-\nu)}\left[\frac{1}{r^2}\int_{r_{\mathrm{w}}}^{r}T^{\mathrm{f}}(r,\ t)r\mathrm{d}r-T^{\mathrm{f}}(r,\ t)\right] \tag{5}$$

$$\sigma_{zz}=\frac{\alpha(1-2\nu)}{1-\nu}P^{\mathrm{f}}(r,t)+\frac{E\alpha_{\mathrm{m}}}{3(1-\nu)}T^{\mathrm{f}}(r,t) \tag{6}$$

where α_{m} is the thermal expansion coefficient; r_{w} is the wellbore radius; E is the modulus of elasticity; $P^{\mathrm{f}}(r,t)$ and $T^{\mathrm{f}}(r,t)$ are the differences of pressure and temperature of a point on the wall at time zero and time t in a place with radius r, respectively.

2.3. Thermo-poroelastic model

In this way, the total amount of stresses around the wellbore can be determined by superimposing of results from Kirsch equations with induced stresses. The following equations which relate to fully coupled thermo-poroelastic condition exhibit the overall stresses around a wellbore:

$$\sigma_{rr}=\frac{\sigma_x+\sigma_y}{2}\left(1-\frac{R^2}{r^2}\right)+\frac{\sigma_x-\sigma_y}{2}\left(1-4\frac{R^2}{r^2}+3\frac{R^4}{r^4}\right)\cos(2\theta)+\tau_{xy}\left(1-4\frac{R^2}{r^2}+3\frac{R^4}{r^4}\right)\sin(2\theta)+\frac{\alpha(1-2\nu)}{1-\nu}\frac{1}{r^2}\int_{r_{\mathrm{w}}}^{r}P^{\mathrm{f}}(r,t)r\mathrm{d}r+\frac{E\alpha_{\mathrm{m}}}{3(1-\nu)}\frac{1}{r^2}\int_{r_{\mathrm{w}}}^{r}T^{\mathrm{f}}(r,t)r\mathrm{d}r+\frac{R^2}{r^2}P_{\mathrm{w}} \tag{7}$$

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