International Journal of Rock Mechanics & Mining Sciences 71 (2014) 418–428

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

Transient thermo-poroelastic finite element analysis of borehole breakouts

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ARTICLE INFO

Article history:
Received 28 August 2013
Received in revised form
26 May 2014
Accepted 5 August 2014
Available online 15 September 2014

Keywords:
Thermoporoelastic
Borehole stability
Breakout stabilization
Failure criteria
Finite element

ABSTRACT

A thermo-poroelastic model which is fully coupled to conductive and convective transport processes is employed to analyze wellbore stability and borehole breakout. Using the two-dimensional finite element method, stress distribution around an open borehole subjected to non-isothermal, non-hydrostatic loading is investigated. Four strength criteria: Mohr–Coulomb, Drucker–Prager, modified Lade, and Mogi–Coulomb, are utilized to the stability of boreholes. Borehole breakout propagation is assumed to occur as successive spalling of thin layers of rock caused by stress concentration and redistribution around boreholes and breakouts. Stabilization of breakouts is examined by deploying Mogi–Coulomb failure criterion for different wellbore fluid pressures and temperatures. To evaluate the influence of various prominent factors on borehole breakouts, a parametric study is conducted. Results indicate that Mohr–Coulomb criterion offers the highest breakout depth, so it underestimates rock strength and requires the highest value of the least mud weight necessary for wellbore stability and Drucker–Prager provides the lowest estimation of the breakout depth. Borehole breakout stabilization is concluded to occur as consequences of reduction in effective tangential stress and increase in confinement effect of radial stress around breakout periphery. Moreover, confinement effect of borehole fluid appears to be more influential in borehole stability than pore pressure effect. Parametric analysis reveals that drilling a borehole with small radii, applying overbalanced fluid pressure condition, and maintaining drilling fluid temperature lower than rock temperature boost the creation of a favorable borehole stability condition.

1. Introduction

Borehole breakouts are changes in borehole geometry in a cross section perpendicular to the borehole axis which is the result of the stress induced spalling of the borehole wall. The first report of rock breakout was made by Leeman [1] from South African gold mine. Same observations of rock breakouts in oil wells were reported by Cox [2]. Later on, Carr [3] pinpointed that borehole enlargement orientation was consistent with the direction of the minimum in-situ horizontal principal stress. Various researchers, like Bell and Gough [4], Zoback et al. [5], and Haimson and Herrick [6,7] verified the hypothesis developed by Carr [3].

Extensive laboratory [6–8], numerical simulation, and theoretical analysis [9–11], have been done to determine whether breakouts can be used to obtain information about in-situ stress magnitudes and to understand certain correlations between far-field principal stress magnitudes and the borehole breakout dimensions. However, breakout initiation and propagation are the results of a series of complex processes that simultaneously affect the borehole wall; therefore, a unique relation between breakout geometry and applied stresses does not exist and there are serious misgivings regarding the accuracy of predicting in-situ stress magnitudes from observed breakouts geometry.

When a borehole is drilled, the original stress field in the rock and around borehole changes and the concentration and distribution of tangential and radial stresses will develop around the borehole. In an elastic material, the largest stress concentration occurs at the wellbore wall. At some specific spots around borehole the combination of these stresses will exceed strength of the rock and develop borehole breakouts or induced fractures. Evidence from experimental, numerical, and field observations [5,11,12] show that two major mechanisms of rock failure, extensile splitting and shear fracturing of rock, are responsible for breakout initiation and propagation. Extensile splitting of the rock occurs when confining pressure is low or zero and shear failure develop under condition of high confining stresses (Zheng et al. [11]). In addition of confining pressure and in-situ stress anisotropy, different rock properties (rock type, mineral composition,

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http://dx.doi.org/10.1016/j.ijrmms.2014.08.008
1365-1609/

grain cementation, and rock failure criteria) and drilling parameters (fluid pressure and temperature, hole size) have great influences on the wellbore stability and failure mechanisms of borehole wall.

Gough and Bell [13] and Zoback et al. [5] applied Mohr–Coulomb failure criterion to the stresses around a circular opening in an elastic material to analyze breakouts and to locate the points where fractures occur around the borehole. Zoback et al. [5] inferred that the use of a simple elastic brittle model to the problem of breakout growth is inaccurate. Afterwards, the results found by Zoback et al. [5] were commented on by Detournay and Roegiers [14] and they stated that major mechanisms regarding borehole failure develop in brittle manner. Zheng et al. [11] studied factors affecting the initiation, propagation, and stabilization of wellbore breakouts in a linearly elastic, homogeneous, and isotropic materials. Their model was limited to boreholes with zero wellbore fluid pressure, so they used unconfined compressive strength of rock along with Mohr Coulomb criterion to investigate breakout initiation a little deeper. The outcomes of Zheng's research [11] were subjected to criticism by Cheatham [15]. He proved that the inclusion of a weakened damaged zone at breakout tip causes a reduction in the stress intensity, which finally stabilizes the breakout.

Wang and Dusseault [16] applied linear thermo-poroelastic concept to calculate tangential stresses around a borehole and discussed conditions of thermal effects on wellbore stability. Han and Dusseault [17] investigated near borehole permeability using poroelastic and poro-inelastic concepts. They defined the region of failed area as Coulomb zone and concluded that the Coulomb zone modeled by poro-inelastic theory is larger. Yuan and Harrison [18] modeled borehole breakouts and associated fluid flow using a hydromechanical local degradation approach. They stated that, using a degradation concept and corresponding changes in hydro-mechanical properties, the continuum-based model is capable of modeling the successive breakout process due to stress redistribution around the borehole by making damaged elements nearly ineffective. Sulem et al. [19] developed a nonlinear elasto-plastic model with mixed hardening/softening for Red Wildmoor sandstone. Later, Papamichos [20] used this nonlinear elasto-plastic constitutive model to investigate the effects of borehole size and stress anisotropy in the borehole failure stress for a Cosserat continuum. The results compared well both qualitatively and quantitatively with experimental results from polyaxial tests on Red Wildmoor sandstone [20]. Haimson [21] conducted a series of experiments to study micromechanisms of borehole breakouts on various rock types and concluded that breakouts can differ widely depending on rock type, mineral composition, and grain cementation.

Almost in all wellbore stability studies the Mohr–Coulomb criterion has played a pivotal role in studying the failure of rocks. There are two major issues related to this criterion. The first one is the assumption of linear relation between minimum and maximum principle stresses. The second one is the assumption that the value of the intermediate principal stress, σ_2, has no influence on the rock strength. Recent evidences [8,22–24] have shown that the intermediate principal stress does indeed have an influence on rock strength. Al-Ajmi and Zimmerman [23–25] developed a new rock failure criterion named as Mogi–Coulomb criterion, which was used to probe the stability of boreholes based on this criterion. Zhang et al. [27] utilized polyaxial strength test data of five rock samples to determine parameters for five rock strength criteria and to study the stability of boreholes drilled into these five rocks. Notwithstanding their attempts, they did not consider either thermal or pore pressure effects in their analysis. All in all, the results for all rocks indicated that the 3D Hoek–Brown and Mogi–Coulomb criteria are the best suited criteria for analyzing wellbore stability.

In this study, a transient thermo-poroelastic model that is fully coupled to conductive and convective transport processes is applied to a linear elastic, homogeneous, and isotropic medium. Plane-strain conditions are assumed in direction of the borehole axis where an axial overburden stress is exerted. A two-dimensional numerical technique using finite element method is developed to model distribution of stresses, fluid pressure and rock and fluid temperature profiles. Knowing stress distribution, different rock failure criteria: Mohr–Coulomb, Drucker–Prager, modified Lade and Mogi–Coulomb criteria are employed to study borehole breakouts. Numerical solution is verified with the available analytical solution of poroelastic medium. Like Zheng et al. [11] and Yuan and Harrison [18], we assumed that the mechanism of wellbore breakout initiation and propagation consists of the successive spalling of rock layers adjacent to the borehole wall. To deeply analyze wellbore breakout stabilization and to study the main factors affecting breakout geometry (i.e. borehole radius, stress anisotropy, fluid pressure and temperature) the Mogi–Coulomb criterion is utilized.

2. Problem description and methodology

2.1. Thermoporoelastic model

The general theory of poroelasticity was introduced by Biot [28], and developed further by Rice and Cleary [29], Detournay and Cheng [30], Cui et al. [31–33], and Santarelli et al. [34]. Constitutive equations for thermoporoelastic theory were first introduced by Palciauskas and Domenico [35] by extending the classic Biot's poroelastic theory for the non-isothermal case. The governing equation considering the theory of thermo-poroelasticity is developed by combining the influences of thermal stress, differential solid and fluid expansion to Navior's equation of stress equilibrium and fluid mass balance equations. Using the geomechanics sign convention of compression positive, the constitutive equation is:

$$G\frac{\partial^2 u_j}{\partial x_i \partial x_i}+(\lambda+G)\frac{\partial^2 u_i}{\partial x_i \partial x_j}-\alpha\frac{\partial p_p}{\partial x_j}-K\beta_s\frac{\partial T}{\partial x_j}-f_j=0 \tag{1}$$

where u is the rock displacement,G and λ are the shear modulus and Lame constant, and p_p and T indicate pore pressure and temperature, respectively. The multipliers α, K and β_s represent the Biot coefficient, drained bulk modulus of poroelastic matrix and drained thermal expansivity of solid, respectively. The term f is the summation of all body forces, and the indices i,j stand for x and y coordinate axes.

The governing equations for the single-phase flow and energy balance of a fluid are given by the conservation of mass and energy, Darcy's law, and equation of state. To perfectly consider effects of all coupling transport phenomenon, the conductive and convective heat transfer and mass fluxes due to dispersion and diffusion are considered. The coupled fluid mass and energy balance equations can be written as:

$$\frac{\partial}{\partial x_i}\left(\frac{k}{\mu}\frac{\partial p_p}{\partial x_i}\right)=\beta\frac{\partial p_p}{\partial t}-\alpha\frac{\partial^2 u_i}{\partial t \partial x_i}+\beta_m\frac{\partial T}{\partial t} \tag{2}$$

$$\frac{\partial}{\partial x_i}\left(k_m\frac{\partial T}{\partial x_i}\right)=(\rho c)_f\frac{k}{\mu}\left(\frac{\partial p_p}{\partial x_i}\right)\frac{\partial T}{\partial x_i}+(\rho c)_m\frac{\partial T}{\partial t} \tag{3}$$

where β, β_m are Biot's modulus and undrained thermal expansivity of saturated rock, respectively; $k$and μ denote rock intrinsic permeability and fluid viscosity; c_f, c_m, ρ_m, ρ_f and k_m represent fluid and rock bulk heat capacity, mean rock-fluid and fluid density and mean rock bulk conductivity, respectively.