



A wellbore stability model for shale formations: Accounting for strength anisotropy and fluid induced instability



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ABSTRACT

The presence of weak planes in rock fabric along with interactions of clay minerals with aqueous fluids are the major causes of instability in shale formations. Reviewing the current state-of-the art of wellbore stability models indicates that the interaction of aqueous fluids with clay minerals has been ignored or over-simplified due to the complexity of the processes. In this paper, a diffusion-sorption model, which is considered to be a unified model for all shale types, is integrated with a wellbore stability model. The coupled transport equations are solved using a finite difference method to determine pore pressure and moisture content in the vicinity of the borehole. The wellbore stability is analyzed using the modified Jaeger's criterion, which considers shale to be an isotropic body containing one set of weakness planes. Using field data, a comparison between the anisotropic failure model and isotropic failure model is presented. The results indicate that the wellbore is less stable when bedding planes are considered. The sensitivity analysis shows that the extent of failure zone in the vicinity of borehole is primarily governed by the orientation of wellbore trajectory with respect to the bedding planes. Furthermore, it is shown that the intrinsic rock strength anisotropy can be a significant parameter for failure analysis when shear failure along the bedding plane is not a major concern. The presented model predicts the instantaneous moisture content around the borehole, which is used as an index for estimation of rock strength both in shale matrix and along weakness planes. The simulation results shows that shale-fluid interaction affects borehole stability at early times.

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1. Introduction

Results of recent survey shows that about one third of non-productive time of drilling operation is classified as borehole problems, where a significant part is attributed to the indicators of borehole instability (Hamayun, 2011). In the case of shale formation, some of the reported difficulties are shale swelling, bit balling, stuck pipe, high torque, and reduction of penetration rate (Labenski and Reid, 2003). To prevent borehole instability, different remedy solutions are recommended. A common approach is to use a higher mud weight to increase the borehole support. In the case of reactive shales, inhibitive drilling fluids containing different chemicals are attempted. In conventional wellbore stability modeling, the rock is assumed to be linear elastic and isotropic in mechanical and

strength properties. However, it is known that the presence of bedding planes and lamination in geological situations imparts anisotropy to mechanical properties of rocks. More specifically, most sedimentary rocks exhibit inherent strength anisotropy. This can be theoretically explained by the presence of bedding plane in rocks (Nova, 1980; Duveau et al., 1998) or a preferred orientation of cracks in rocks (Walsh and Brace, 1964). The first approach has been studied for predicting rock failure while drilling in underground structures. Numerous studies have been published about the anisotropic strength behavior of various rock types (Chenevert and Gatlin, 1965; Nova, 1980; Fjær and Nes, 2013). Extensive research has been conducted in characterization of anisotropic behavior of shale formations. The effect of shale bedding plane failure on wellbore stability has been recognized for inclined wells (Okland and Cook, 1998; Willson et al., 1999; Edwards et al., 2004; Wu and Tan, 2010; Fjær and Nes, 2013). Okland and Cook (1998) reported that borehole instability is related to strength anisotropy associated with a noticeable bedding plane in shale formations. The

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reported laboratory results confirmed the field experiences, indicating that the borehole instability is not significant when drilling normal to the bedding planes, but becomes very severe when the hole is parallel or nearly parallel to the bedding planes. However, the authors could not explain the growth of the failed zone in the case of drilling parallel to the bedding plane using an aqueous fluid. Willson et al. (1999) investigated few cases of wellbore instability problems associated with complex geologic conditions in South America. The case study revealed that bedding-plane slippage is a major cause of wellbore instability. Edwards et al. (2004) combined the results of Logging-While-Drilling (LWD) with observation of cuttings to diagnose the mechanism of instability for a given field in the Gulf of Mexico. They concluded that the presence of weakness planes could dominate the failure mode of shale. It is reported that the majority of wellbore instability is caused by low attack angle to the bedding plane and the penetration of mud into pre-existing weakness planes. However, it is stated that increasing the mud weight (which usually prevents shear failure in isotropic rocks) can deteriorate the collapse mode. Ghajari et al. (2013) identified the borehole instability due to drilling orientation with respect to weakness plane in one of offshore fields in the Middle East. The authors concluded that an optimized drilling orientation is more helpful rather than a chemical remedy.

A natural consequence of lamination is that the mechanical properties of rock becomes anisotropic. Tri-axial compression tests conducted at different bedding orientation (the angle between normal to the bedding and maximum principal stress is denoted by β) indicate that the maximum strength occurs at angles of $\beta = 0^\circ$ or $\beta = 90^\circ$, while the minimum strength occurs between 30° and 60° , as reported by: Chenevert and Gatlin, 1964; Duveau et al. (1998); Ajalloeian and Lashkaripour (2000); and Fjær and Nes (2013). Several investigators defined various indices to identify the strength anisotropy of sedimentary rocks, including Duveau et al. (1998), Ajalloeian and Lashkaripour (2000), and Ambrose et al. (2014). For example, the strength anisotropy ratio is defined as the ratio of the maximum compressive strength to the minimum compressive strength at a given confining pressure. Duveau et al. (1998) stated that with an increase in confining pressure the strength anisotropy decreases. The authors also suggested to use a discontinuous weakness plane model for strongly anisotropic materials.

In addition, drilling fluids can affect borehole stability in shale formations. Specifically, the increase in moisture content of the rock due to interaction with aqueous fluids has been shown to have a negative effect on the compressive strength of the rock (Chenvert, 1970; van Oort et al., 1996). Several empirical correlations have been proposed to describe the relation between compressive strength and moisture content of shale formations. The common theme among these correlations is that the uniaxial compressive strength is reduced exponentially as the moisture content increases (Lashkaripour and Passaris, 1995; Hsu and Nelson, 2002; AL-Bazali, 2013). In addition, Colback and Wiid (1965) reported that the compressive strength of quartzitic sandstone is inversely proportional to the surface tension of liquids with which the samples are saturated. According to Lama and Vutukuri (1978), other factors such as the pH value of the aqueous solution and temperature of the environment can also affect to some degree on the rock strength.

The complete analysis of shale instability is a complicated process, and the available models are based on over-simplification to describe the phenomenon. The problem was first modeled by neglecting the effect of fluid propagation around the borehole, i.e. the pure elastic models. Early models were based on the assumption of isotropic rock failure (Bradley, 1979; Aadnoy and Chenevert, 1987). Later, the models were modified to include the fluid induced

stresses (Detourney and Cheng, 1988; Yew and Liu, 1992). For wellbore stability analysis of shale formations, researchers in the last decade attempted to investigate the chemical effects and thermal effects separately through mathematical modeling (Yu et al., 2003; Shahabadi et al., 2006). In addition, there are several papers in which, the fluid induced stresses due to chemical and thermal gradients are linearly added (Zhang et al., 2006; Roshan and Osereb, 2011; Rafieepour et al., 2015). However, it should be advised that a rigorous assumption before calculating the chemical effect is the isothermal condition. Thus, a linear superposition of chemical and thermal effects may not accurately describe the problem. In recent years, wellbore stability analysis has been investigated further in order to examine special problems. For example, a method for analysis of wellbore stability in fractured shale rocks is presented by Nguyen et al. (2007), in which the pore pressure variation in fracture and matrix is combined in the governing equation. Chen et al. (2015) investigated the time-dependent effect of mud loss on wellbore stability.

In summary, one of the major assumptions among all the proposed wellbore stability models is that the interactions between aqueous fluid and shale matrix are neglected. In other words, the proposed models only concern about the interactions between the drilling fluid and the pore fluid through the chemical osmosis process and the contribution of shale matrix is reflected with a so-called “membrane efficiency”. Hence, the physical changes of the rock matrix during the interaction process cannot be directly addressed. As a result, by neglecting the interactions the reliability of the model is compromised. Although ignoring the interactions by previous investigators allows development of various scenarios for analytical modeling, yet a unified model that can be concluded for all shale rocks has not been developed. Furthermore, effect of strength anisotropy on borehole failure has not received proper attention in the modeling approaches. In brief, the above discussion provides enough motivation to revisit the wellbore stability modeling in shale formation.

2. Theory

2.1. Transport equations

To describe the restrictions of the model, the following assumptions should be declared: (1) shale rock is anisotropic and unbounded and the fluid flow around the borehole occurs radially, (2) a set of weak bedding plane exists in which the strength is lower than the intrinsic rock, (3) shale is assumed to be fully saturated due to its burial depth, (4) the problem is investigated under linear elasticity and isothermal conditions, (5) transport coefficients are constant. Due to ultra-low permeability of shale formations, flux of fluid components are usually expressed in analogy to membranes. Dokhani et al. (2015a) reviewed the transport models in shale formation and suggested to establish the governing equations based on moisture content. Accordingly, the effects of chemical potential imbalance is expressed through the continuity equation as follows:

$$\frac{\partial w}{\partial t} = D_w^{eff} \left(\frac{\partial^2 \text{Lna}_w}{\partial r^2} + \frac{1}{r} \frac{\partial \text{Lna}_w}{\partial r} \right) \quad (1)$$

where D_w^{eff} is the diffusivity coefficient. Note that Eq. (1) requires an auxiliary equation to be solved. It is assumed that the sorption phenomenon is instantaneous when compared with the diffusion process. The terminology of sorption is preserved which includes both adsorption and desorption phenomena. For instance, when water activity of drilling fluid is higher than that of shale, the

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