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A wellbore stability analysis model with chemical-mechanical coupling for shale gas reservoirs

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ABSTRACT

Chemical and mechanical coupling are the most important factors affecting wellbore instability. The main objective of this research is to propose a wellbore stability analysis model for shale gas reservoirs. A mathematical model was proposed to analyze wellbore stability based on a quantitative solution for stress induced by mechanical, hydraulic and chemical effects, and the effective stress tensor around the borehole in a cylindrical coordinate system was also obtained. Anisotropic mechanical properties and changes in the strength of shale rocks were collected from tri-axial compression experiments, direct shear tests and the literature. To examine for shear failure along the weak plane and across the weak plane, the effective stress tensor in a cylindrical coordinate system was transformed into the weak plane's local coordinate system and integrated into the strength criteria of the weak plane. In addition, the failure regions around a horizontal well were simulated at different drilling times and for different drilling directions, and the real causes of wellbore instability for well X201-H1 in the Sichuan basin were analyzed. The results indicate that the nonlinear evolution equation for the strength parameters obeyed the logistic model; the strength parameters decreased drastically as the soaking time increased over the first five days, after which the strength parameters decreased slowly. In addition, pore pressure increased and solute concentration decreased under the condition $C_m < C_0$, while pore pressure decreased and solute concentration increased under the condition $C_m > C_0$. The decrease in strength and the increase in pore pressure have significant impacts on the stability of wellbores within shale gas reservoirs. Pore pressure propagation changes the effective normal stress on the weak plane of the wellbore and results in the stress concentration exceeding the strength envelope. In traditional models, failure regions occur only on the surface of a borehole; however, in the new model, failure regions can also occur in the interior of a formation, and they can occur within four zones around a wellbore's circumference. The decrease of shale strength and the increase of pore pressure under the condition of water-based mud (WBM) has a greater impact than in oil-based mud (OBM), which help define the critical equivalent mud weight (CEMW) requirements at which the rate of collapse increases rapidly. To maintain borehole stability, a series of approaches must be adopted, including reasonable mud weight (MW), mud system, well path, physical plugging, etc. This model can be used to analyze the failure regions around boreholes and calculate the CEMW needed to maintain wellbore stability at different times. This model is different from, and more practical than, the traditional model.

1. Introduction

Shale gas, an unconventional natural gas produced from organic-rich shale, has been paid increasing attention in recent years (Zou et al., 2010; Wang et al., 2013). A new official report from the EIA (2014) has indicated that shale gas resources are abundant around the world, and shale gas has the potential to play a critical and decisive role in the global energy market in the future (Yuan et al., 2014). Shale gas resources are also abundant in China and have already been identified in certain areas. The technically recoverable resources in China have been estimated between 10×10^{12} m^3 and 15×10^{12} m^3 (Wang et al., 2013). Because the native permeability of shale gas is extremely low, horizontal well

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drilling and hydraulic fracturing are typically used to enhance the recovery of these hydrocarbon resources (Wang et al., 2013; Yan et al., 2014; Ma and Chen, 2014a). However, shale gas reservoirs are often characterized by tight matrix, well-developed bedding planes and micro-fissures, and they are rich in clay mineral, which makes them robustly anisotropic and highly water-sensitive (Ma and Chen, 2014a; Yan et al., 2014). The borehole instability problems that often occur in shale bedding planes rich in clay minerals are often associated with equivalent mud weight (EMW, either static or circulating equivalent density), in situ stress, wellbore orientation, and chemical reactions, among other things. The single most important cause of wellbore instability is incorrect EMW (Fjar et al., 2008; Chen et al., 2008a; Zoback, 2012; Lee et al., 2012). Too low of an EMW can cause shear failure around the borehole, which can lead to cave-ins and hole collapses; too high an EMW can cause tension failure around the borehole, which can lead to lost mud or lost circulation.

Maintaining wellbore stability is an important issue in the oil and gas industry because problems with borehole instability can significantly increase drilling NPT (non-productive time), the length of the drilling cycle, and drilling costs and can decrease the efficiency of exploration and development (Aadnoy and Ong, 2003; Fjar et al., 2008; Chen et al., 2008a; Kang et al., 2009; Zoback, 2012; Yan et al., 2014). With these factors in mind, the purposes of researching wellbore stability are (1) to reduce well construction costs by eliminating borehole instability related to the NPT, (2) to optimize the design of a well's trajectory on the basis of in situ stress and rock properties, and (3) to provide guidelines for the design of the mud weight (MW) used to drill each well in order to keep the borehole from failing during and after drilling. Various researchers have proposed wellbore stability analysis methods, all of which assume that rock is linear elastic and has isotropic strength (Bradley, 1979; Cheatham, 1984; Zoback et al., 1985; Zhou et al., 1994; Aadnoy and Ong, 2003; Fjar et al., 2008; Chen et al., 2008a; Kang et al., 2009; Zoback, 2012; Lee et al., 2012). However, because the anisotropic nature of shale gas reservoirs, the propagation of pore pressure and the chemical reactions therein are ignored, these methods may result in incorrect wellbore stability results when applied to wellbores in shale gas reservoirs. Aadnøy (1987) proposed a semi-analytical model to study the effects of anisotropic strength, borehole inclination, in situ stress, etc., to solve the issues of wellbore instability that result from drilling in formations with anisotropic rock strengths. The results of that study indicated that rocks would fail along weak planes under certain conditions, which had significant effects on wellbore stability. Following Aadnøy, various researchers proposed new methods to determine wellbore stability by assuming that rocks were transversely isotropic materials with anisotropic strength behaviors (Aadnøy and Chenevert, 1987; Aadnøy, 1988; Ong and Roegiers, 1993, 1996; Ong, 1994; Okland and Cook, 1998; Gupta and Zaman, 1999; Zhang, 2008, 2009; Chen et al., 2008a,b; Pei, 2008; Al-Bazali et al., 2009; Younessi and Rasouli, 2010; Tan et al., 2010; Jin et al., 2013; Hou et al., 2013; Zhang, 2013). Their works indicated that neglecting the effects of anisotropy could result in incorrect results. Despite these efforts to modify the wellbore stability models, numerous accidents associated with wellbore instability in shale gas reservoirs have been reported (Yan et al., 2013, 2014; Ma and Chen, 2014a,b,c). Zoback (2012) and Lee et al. (2012, 2013) found that the shapes and orientations of failure regions are significantly affected by anisotropic strength, and a few researchers have also studied the influence of anisotropic strength on instability regions around the borehole (Lee et al., 2012, 2013; Ma and Chen, 2014b). In addition, a few researchers have investigated the influence of multiple weak planes (Liu et al., 2014; Chen et al., 2014a). However, none of these models have considered the impact of mechanical and chemical coupling on wellbore stability. Some researchers have addressed this issue; however, most of them have only focused on hydro-mechanical coupling or thermo-hydro-mechanical coupling (Cui et al., 1997; Abousleiman and Cui, 1998; Ekbote, 2002; Yuan et al., 2013, 2014). And while a large number of researchers have studied the influence of mechanical and chemical coupling on wellbore stability related to hydration and interactions with drilling mud (Chen et al., 2003a; Cheng et al., 2006; Lu et al., 2012, 2013; Li et al., 2012a; Yan et al., 2013; Ma and Chen, 2014a), these researchers have still failed to consider the influence of comprehensive factors such as wellbore inclination, anisotropic in situ stress, anisotropic rock strength, mechanical and chemical coupling, downhole pressure (or EMW), the changes in the shale strength, etc., on the unstable zone around the borehole or the critical collapse pressure. Therefore, the main objective of this research is to propose a semi-analytical model and method of wellbore stability analysis for shale gas formations, in which the rock material is assumed to be poroelastic, have anisotropic strength behaviors and have variable strength, while the multi-field coupling is assumed to be both mechanical and chemical; in addition, the anisotropic elasticity behavior and dynamic conditions of wellbore pressure are ignored.

2. Chemical-mechanical collapse pressure model for shale

2.1. The propagation of pore pressure

Wellbore collapse occurs when exposure to mud causes the propagation of pore pressure (Mody and Hale, 1993; Yu et al., 2001; Yu, 2002; Van Oort, 2003; Yu et al., 2003; Chen et al., 2003b, 2010; Zeynali, 2012). Mody and Hale (1993) assume that shales can act as semi-permeable membranes, with hydraulic pressure, osmotic pressure and electrical potential gradients acting as the driving forces on those membranes. However, electrical potential gradients are generally seldom taken into account in pore pressure propagation models, leaving hydraulic pressure and osmotic pressure gradients as the driving forces in these models, where the equation of osmotic pressure is expressed as (Mody and Hale, 1993),

$$p - p_0 = I_m \frac{RT}{V} \ln\left(\frac{a_{shale}}{a_{mud}}\right) \tag{1}$$

where p is pore pressure, MPa; I_m is membrane efficiency; T is the absolute temperature, K; R is the perfect gas constant; V is the partial molar volume of water, l/mol; a_{shale} is the activity of water for pore fluid; a_{mud} is the activity of water for drilling mud; and p_0 is the original pore pressure, MPa.

2.1.1. General equation for water transport in shales

Solvent transport is driven by hydraulic pressure, osmotic pressure gradients, as well as changes in solute concentration and pore pressure. As a result, the solvent flux equation can be expressed as (Yu et al., 2001; Yu, 2002),

$$J_v = -k_1 \nabla p - nRTk_2 \nabla C_s \tag{2}$$

where J_v is the solvent flux, l; k_1 is the hydraulic diffusion coefficient, $m^2/(Pa\ s)$; k_2 is the membrane efficiency, $m^2/(Pa\ s)$; n is the mole number of solute ions; and C_s is the solute concentration of pore fluid, mol/l.

According to the principle of mass conservation, the conservation of mass applied to the solvent can be expressed as (Yu et al., 2001; Yu, 2002),