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Mechanical and physico-chemical aspects of wellbore stability during drilling operations

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A B S T R A C T

One of the problems during drilling operation is wellbore instability. Many parameters affect the wellbore stability. Some of these parameters are related to the properties of drilling mud and its interaction with the formation and some of them are related to the mechanical properties of the formation and the magnitude and distribution of the forces around the wellbore. Generally the wellbore instability is calssified as mechanical, physico-chemical or both. This paper is an attempt to investigate the mechanical and physico-chemical aspects of wellbore stability during drilling operations

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1. Introduction

It is estimated that wellbore instabilities have resulted a loss of about US$ 1 billion per year worldwide. Maintaining wellbore stability is a key factor in improving safety and drilling efficiency while minimizing problem costs associated with well construction and production operations. Wellbore stability is the determination of the conditions under which failure will initiate in the rock surrounding the wellbore. The key in the analysis is that when a well is drilled the rock surrounding the hole must take the load that was previously taken by the removed rock. As a result an increase in stress around the wall of the hole, a stress concentration is produced. If the rock is not strong enough the borehole will fail. A common operational approach to wellbore stability problems is the drillers method of trial and error based on field observations and experience. Considerable effort has been directed towards solving rock mechanics problems associated with wellbore instabilities through providing predictive methods (Zhou et al., June, 1996; Zhang et al., 2003), understanding and quantifying shale mechanical behavior (Steiger and Leung, 1992), development of theoretical concepts (Bradley, 1979a, 1979b; Zobak et al., 1986; and Vardoulakis et al., 1988; Moos et al., 2003) and experience in field applications (Maury and Sauzay, 1987). According to the field experience and theoretical interpretation the causes of instability are often classified into either chemical or mechanical effects or combination of both. Special issue on borehole stability has been addressed in the literature (Aadnoy, 2003). Various parameters influence the wellbore stability and depending on relative importance should be considered in modeling and analysis. This paper is an attempt to briefly review the mechanical and physico-chemical aspects of wellbore stability and most important factors influencing the wellbore stability during drilling operations.

2. Mechanics of borehole stability

Mechanical instabilities are caused directly by drilling operation. Removal of the cylindrical material induces a stress concentration around the wellbore which usually can be balanced by hydrostatic pressure of drilling mud. The mechanics of borehole stability have been analyzed mathematically using analytical and numerical methods by numerous authors and many publications can be found in the literature (McLean and Addis, 1990; Tan and Willoughby, 1993; Zhou et al., June, 1996; Wang and Dusseault, 2003; Coelho et al., 2005; Zhang et al., 2006).

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When a borehole is drilled into the rock, the stresses are redistributed around the hole. If the stresses are high enough so as to exceed a yield criterion, a yield zone can appear around the borehole. Linear elastic stress analysis is frequently used as a method of computing the stress state around a wellbore due to its simplicity of the analysis. A support pressure or drilling fluid density that will prevent instability can be calculated by assuming a linear elastic stress concentration around the hole and maintaining these stresses below the rock strength (Bradley, 1979a, 1979b; and Steiger and Leung, 1990). Although this approach is convenient but is often conservative due to non-linear and inelastic rock behaviors. The linear elastic model underestimate fracture pressures measured on hollow concrete cores. The uncertainty in the predicted critical mud weights associated with the estimated in-situ stress magnitudes and material properties, and the linear elastic analytical method can be reduced by calibrating the predicted mud weights with reference mud weights based on drilling experience (Tan and Willoughby, 1993). Elasto-plastic fracturing model for wellbore stability using non penetrating fluids has been introduced (Aadnoy and Belayneh, 2004). Also poroelastic models which consider pore pressure changes within the rock have been used for wellbore stability analysis. Confining pressure dependent models describing stress concentrations around circular openings provide better predictions of yield than do linear elastic solutions, when compared to model tests (Santarelli et al., 1986). This model considers the strengthening of the rock due to confining pressure. However, the main basis for this assumption is hollow tests, which may be subject to scale effects relative to full scale wellbores. Shale mechanics in conjunction with numerical analysis, such as the finite element method, can lead to greatly improved wellbore stability predictive capabilities (Mitchel and Goodman, 1987; Zhou and Gassemi, 2009).

When determining the stability of the wellbore, the computed stresses must be compared with a failure criterion. A main mechanical aspect of wellbore stability analysis is the selection of an appropriate rock failure criterion. The most commonly used criterion for brittle failure of rocks is the Mohr–Coulomb criterion. The criterion involves only the maximum and minimum principal stresses and therefore assumes that the intermediate stress has no influence on rock strength. Al-Ajmi and Zimmerman (2006) developed the Mogi–Coulomb failure criterion and showed that it is reasonably accurate in modeling polyaxial failure data from a variety of rocks. It neither ignores the strengthening effect of intermediate principal stress as is done by the Mohr–Coulomb criterion, nor does it predict a strength as unrealistically high as does the Drucker–Prager criterion. Coelho et al. (2005) presented a comparison among Drucker–Prager, Mohr–Coulomb and cap model in wellbore stability analysis for a borehole drilled in 30% porosity limestone from a deep water reservoir. Stability analysis of a horizontal wellbore drilled in the same reservoir was done. Drucker–Prager shear model presented shear failure during drilling, while Mohr–Coulomb shear model presented no failure.

A comprehensive list of the factors that may influence wellbore instability is given by McLean (1988) and Chen et al. (1997). A wellbore stability model that includes all factors will be very complex. The complexity can be reduced when the model is developed in relation to the location of the well under consideration.

Therefore consideration should be given to the relative importance of the parameters involved. Some of the theoretically identified and most important factors that affect mechanical wellbore stability are:

(1) in situ stresses existing in different layers of rock
(2) the mechanical properties of rock
(3) variation of pore pressure
(4) mud weight
(5) hole angle and direction
(6) thermal effects and
(7) anisotropy.

The various analytical tools which provide insight into wellbore stability require knowledge of in-situ stresses and response of the rocks to the stress changes imposed by drilling operation. In order to predict whether the walls of a proposed well will be stable or will spall, it is necessary to specify the far field in situ stresses that will be experienced by the wellbore. For example controlling of stress-induced wellbore instability and designing of the deviated and horizontal wellbores require knowledge of the magnitude and orientation of the in-situ stress field (Tan et al., 1993). Hydraulic fracturing is the widely accepted technique for the determination of in-situ stress magnitude from a wellbore. The method essentially consists of pressurizing an isolated section of a vertical wellbore until the rock strength and the concentrated tectonic stresses overcome.

Bell (2003) outlined how to estimate stress orientations and magnitudes with average data suites and it alludes to mapping applications. Zoback et al. (2003) reviewed a suite of techniques for determination of in situ stress orientation and magnitude in deep wells and boreholes. As these techniques can be utilized in both vertical and highly deviated well, they have had extensive applications in petroleum industry where knowledge of orientation and magnitude at depth is important for addressing a wide range of problems. In situ stresses analysis based on the identification of compressive and tensile failures of the borehole wall in electrical and acoustic borehole imaging logs carried out by Brudy and Kjorholt (2001) on Norwegian continental shelf. This method for the determination of the stress orientation is found to be highly reliable and capable of delivering detailed and accurate results, and thus is far superior to the analysis of breakouts from four-arm caliper logs. The influence of the in situ stress regime on wellbore stability varies with the relative magnitude between vertical stresses, maximum and minimum horizontal stresses rather than their absolute magnitude. Unequal horizontal principal stresses in near vertical boreholes commonly cause localized spalling of the wall-rock in a direction parallel to that of the minimum compressive stress. Consideration of stress field around a arbitrarily oriented borehole shows that in an extensional stress regime ($\sigma_v > \sigma_H > \sigma_h$), wellbore parallel to the direction of minimum horizontal principal stress are the least prone to compressive shear failure (breakout). The most stable deviation angle (from the vertical) depends on the ratio of the horizontal principal stresses to the vertical stresses, and the higher the ratio σ_H/σ_v, the higher the deviation angle for minimizing breakout. In a strike-slip stress regime ($\sigma_H > \sigma_v > \sigma_h$) horizontal wells are the least prone to breakout, and the higher the ratio σ_H/σ_v, the closer the drilling direction should be to the azimuth of σ_H.

The mechanical properties of rock influence the wellbore stability. Generally, two methods: direct laboratory measurement, and indirect well logging interpretation are used to determine rock mechanical properties. The direct method is more accurate if was run by using proper laboratory techniques, but it is expensive and time consuming. Furthermore, it is difficult to obtain a complete formation strength profile without running many tests. The indirect method predicts rock strength by acoustic log data and log/strength correlations. One limitation of this method is that it requires accurate experimental data to establish correlations between strength and velocity (Al-Bazali et al., 2008a, 2008b).

The role of pore pressure in failure phenomena is evident in soil mechanics. Unstable slopes along highways after heavy rains and catastrophic land slides in open-pit mining operations serve to illustrate the important role of pore pressure. In rocks, the same effects exists but is less easily observed. A triaxial compression cylinder of rock fails at decreasing stresses as the pore pressure is increased to the confining pressure. Under the same dimensional and boundary conditions, the tangential stress induced in the cylinder would assume its highest values for a porous cylinder with a permeating fluid of constant viscosity, and its lowest values for an impermeable cylinder; the difference in stresses developed in permeable and impermeable cylinders could be quite significant. For example, rock cylinders at elevated stress levels loaded uniaxially to a stress less than the yield strength can be fractured by holding the constraints constant and