Journal of Petroleum Science and Engineering 135 (2015) 185–200

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Application of quantitative risk assessment in wellbore stability analysis

Raoof Gholami [a,*], Minou Rabiei [b], Vamegh Rasouli [b], Bernt Aadnoy [c], Nikoo Fakhari [d]

[a] Department of Petroleum Engineering, Curtin University, Malaysia
[b] Department of Petroleum Engineering, University of North Dakota, USA
[c] Department of Petroleum Engineering, University of Stavanger, Norway
[d] Department of Chemistry, Shahrood University, Iran

ARTICLE INFO

Article history:
Received 11 December 2014
Received in revised form
11 August 2015
Accepted 10 September 2015
Available online 14 September 2015

Keywords:
Failure criteria
Quantitative risk assessment
Maximum horizontal stress
Sensitivity analysis

ABSTRACT

Elastic and strength parameters, together with pore pressure and in-situ stresses are key parameters required to be known for determination of safe mud weight window (MWW) in vertical wellbores. Estimation of these parameters, however, is subjected to wide uncertainties mainly due to lack of adequate calibration information including lab and field test data. While there are literatures on the applications of probabilistic and risk analysis on wellbore stability evaluation, limited numbers of publications report on the impact of the chosen failure criteria in estimation of safe MWW under uncertain condition. In this study, data corresponding to a wellbore located in south part of Iran was analyzed using quantitative risk assessment to consider the effect of uncertainty on estimation of safe MWW using different failure criteria. The results indicated that Mogi–Coulomb and Hoek–Brown are more robust against the uncertainty of input parameters and mud weight used for this wellbore could have slightly been increased to reduce the shear failure of the borehole wall. The uncertainty in the input data might also be very critical for casing design when only a simple margin together with pore and fracture pressures are used to select the grade of the casing against burst or collapse loads.

It was also noted based on sensitivity analysis that the maximum horizontal stress is the most effective parameter in estimation of MWW. This emphasizes the importance of a reliable estimation of in-situ stresses for safe drilling. The results presented here are based on a single case study, and further studies are still required to get any ultimate conclusion.

1. Introduction

In drilling operations, a proper mud weight needs to be used in order to avoid wellbore instability. The input data used to estimate a safe Mud Weigh Windows (MWW) for drilling practice includes rock elastic and strength properties as well as pore pressure and in-situ stresses (Aadnoy and Looyeh, 2010). In practice, the input parameters are determined using log based analysis and calibrated against core and field data (Rasouli et al., 2011). However, the input data are subject to uncertainty due to limited number of calibration points acquired because of technical or financial constraints. According to Aadnoy (2011), the results of wellbore stability analysis may be uncertain due to lack of calibration data and poor interpretation of in-situ stresses. Therefore, MWW obtained from deterministic analysis is subject to a high degree of uncertainty which needs to be quantified before making any recommendations. This has raised the need in developing probabilistic methods for prediction of MWW and performing wellbore stability analysis.

A statistical approach based on Quantitative Risk Analysis (QRA) has been presented in the last decades to provide a means to assess uncertainty associate with the input datasets used for determination or prediction of many petroleum related parameters (Moos et al., 2003). A large number of literature have reported the use of probabilistic analysis in petroleum related applications ranging from drilling exploratory prospects (Cowan, 1969), optimum casing setting depth selection (Turley, 1976), directional drilling (Thorogood et al., 1991), wireline operations (Sam et al., 1994), special remedial operations (Cunha, 1987), and prediction of pore pressure and fracture gradient (Liang, 2002).

Limited work is however available on applications of risk analysis methods in drilling. Morita (1995) was the first one who published the results of a study on the effects of uncertain parameters on the wellbore stability analysis. He used a derivative based uncertainty assessment for probabilistic analysis of mud loss and break-out prediction. Dumans (1995) applied Monte-Carlo

* Corresponding author. Fax: +60 85443837.
E-mail address: Raoof.Gholami@Curtin.edu.my (R. Gholami).

http://dx.doi.org/10.1016/j.petrol.2015.09.013
0920-4105/

simulation and Fuzzy sets methodologies to estimate the uncertainty of wellbore collapse and tensile failures. Later, Ottesen et al. (1999) presented his model for assessment of uncertainties in break-out pressure prediction using operationally tolerable limits. Liang (2002) considered tensile failure as the upper limit and pore pressure as the lower limit of mud weight to present a complete scheme of risk analysis in wellbore stability studies. Moos et al. (2003) presented an uncertainty analysis for borehole stability and did a sensitivity analysis for determination of key input parameters. Later, Sheng et al. (2006) used Monte-Carlo simulation and numerical model to predict the MWW. Luis et al. (2008) compared deterministic and probabilistic analysis for safe drilling. Aadnoy, (2011) did a wellbore stability analysis by quantifying the uncertainties in mud weight prediction. Mostafavi et al. (2011) presented an approach for wellbore stability analysis using analytical models. Udegbunam et al. (in press) indicated the importance of risk analysis in wellbore stability studies and used Monte-Carlo simulation to determine the risk involved in estimation of pore pressure, strength and in-situ stress parameters. However, there are few studies on the application of different failure criteria in determination of MWW under uncertain conditions. For instance, Al-Ajmi and Al-Harthy (2010) did a study on the applications of Mogi–Coulomb and Mohr–Coulomb failure criteria in determination of mud weight collapse pressure in vertical and deviated boreholes. However, they did not estimate the input parameters required for the analysis and rather used some predetermined values.

In this paper, the QRA is applied to consider the uncertainty of input parameters in determination of MWW when different failure criteria are used.

2. Quantitative risk assessment

Quantitative Risk Assessment (QRA) is one of the most commonly used probabilistic analysis approaches introduced by Ottesen et al. (1999) for oil and gas drilling applications. In the QRA technique, errors involved in input parameters is firstly evaluated and quantified by selecting a suitable distribution function. This is followed by considering an appropriate constitutive model to relate input parameters to desire output. Once the constitutive model is identified, thresholds between failure and success are specified according to Limit State Function (LSF) and a response surface is built using iterations. This response surface is applied to obtain a likelihood of success (LS) by quantifying uncertainty involved in estimation of input and output parameters using probabilistic distribution functions (Aadnoy and Looyeh, 2010). The latter step can be done using an interactive numerical simulation method such as Monte-Carlo technique. Monte-Carlo simulation has been replaced by traditional deterministic methods in petroleum industry to quantify the uncertainty included in any input datasets. According to Murttha (1997), Monte-Carlo simulation is a statistical analysis yielding the probability and relationship of key parameters. It has been used recently for hydrocarbon production forecast (Murttha, 1997), well control (Arlid et al., 2009), well time and cost estimation (Adams et al., 2010) and underbalance well planning (Undebunam et al., 2013).

2.1. QRA applied to wellbore stability analysis

To maintain wellbore stability, the mud weight used to drill the well should be between break-out and induced fracture pressures limits. Wellbore collapse pressure which is also known as break-out pressure is the mud pressure required to avoid wellbore failure in shear mode which is induced due to excessive tangential stresses around the wellbore wall exceeding the rock strength. Generally speaking, as the mud weight decreases, probability of breakout incident increases. On the other hand, high mud weights increase the risk of lost circulation and fracturing the formation. In both of break-out and induced fracture cases, distributions function are fitted to input parameters such that 99% of values lie between maximum and minimum of the curves fitted to them. Once uncertainty of input parameters is specified, response surfaces for wellbore break-out and fracture pressures can be defined. These response surfaces are quadratic polynomial functions of input parameters and their unknown coefficients can be determined by linear regression analysis. These theoretical values are calculated for various combinations of input parameters by taking samples from their distributions. After determination of the response surfaces, Monte-Carlo simulation can be efficiently used to establish uncertainty analysis for wellbore stability to see the possibility of success and failure under given indeterminate condition (Aadnoy and Looyeh, 2010).

3. Key input parameters for wellbore stability analysis

The input parameters considered as the key variables for quantitative risk assessment of borehole stability are elastic parameters (Young's Modulus and Poisson's ratio), Uniaxial Compressive Strength (UCS), pore pressure (P_p), principal in-situ stresses (i.e. σ_v, σ_H, σ_h), borehole inclination, its azimuth and geometry as well as mechanical properties of bedding plane (Aadnoy and Looyeh, 2010; Zhang, 2013; Han and Meng, 2014). By estimation of these parameters and utilizing a constitutive model, a relationship can then be established through different failure criteria for determination of safe MWW using QRA. The principles and correlation used for estimation of these input parameters which also used in this study have been presented in the literature (e.g. Maleki et al., 2014).

4. Constitutive models

4.1. Limit state and probability failure functions

The wellbore stability analysis is a combination of conventional analytical models calibrated against the operational thresholds obtained from in-situ tests including facture tests. These thresholds can be used to determine the possibility of failure and success together with generating a limit state function (LSF) formulated as below:

$$f_L(X) = f_C(X) - f(X) \tag{1}$$

where f is basic failure function obtained from a deterministic analysis, f_C is critical failure function and f_L is LSF function value of the same input parameters. The parameter X is stochastic vector representing key input parameters involved in stability analysis (Ottesen et al., 1999). It should be noticed that depending on which failure criterion is used, the input parameters may be different.

According to Ottesen et al. (1999), the critical failure occurs when:

$$f_L(X) \leq 0 \tag{2}$$

The value of LSF is not usually known for drilling operations as there is no direct equation available to estimate it. However, Monte-Carlo approach can be applied for point-by-point evaluation of this state function with different random values.

Using Monte-Carlo approach and defining a probability failure function according to the key input parameter (X) as below: