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A population-feedback control based algorithm for well trajectory optimization using proxy model

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ABSTRACT

Wellbore instability is one of the concerns in the field of drilling engineering. This phenomenon is affected by several factors such as azimuth, inclination angle, in-situ stress, mud weight, and rock strength parameters. Among these factors, azimuth, inclination angle, and mud weight are controllable. The objective of this paper is to introduce a new procedure based on elastoplastic theory in wellbore stability solution to determine the optimum well trajectory and global minimum mud pressure required (GMMPR). Genetic algorithm (GA) was applied as a main optimization engine that employs proportional feedback controller to obtain the minimum mud pressure required (MMPR). The feedback function repeatedly calculated and updated the error between the simulated and set point of normalized yielded zone area (NYZA). To reduce computation expenses, an artificial neural network (ANN) was used as a proxy (surrogate model) to approximate the behavior of the actual wellbore model. The methodology was applied to a directional well in southwestern Iranian oilfield. The results demonstrated that the error between the predicted GMMPR and practical safe mud pressure was 4% for elastoplastic method, and 22% for conventional elastic solution.

1. Introduction

Well trajectory and mud weight are important factors in the analysis of wellbore stability. Wellbore instabilities during drilling can cause significant problems, about US$500 million is lost each year worldwide. In order to fully obtain the benefits of the directional drilling technology, wellbore stability analysis is necessary in the planning stage of the wells (Chen et al., 1996). A minimum mud weight is required to prevent the near borehole shear failure causing substantial and expenditure impacts. In other words, applying a mud weight larger than the minimum value reduces the rate of penetration and potentially induces formation damage, so addressing the mentioned problem by using a minimum mud weight is essential (Yi et al., 2006).

Normal and shear stresses acting on the rock in the near-wellbore region are functions of inclination angle and azimuth. Unlike the rock properties and far-field principal stresses, wellbore trajectory is a controllable factor for drilling engineers. Accurate design of wellbore trajectory during well planning may help to avoid/reduce borehole failure in the drilling operation (Awal et al., 2001). The effect of azimuth and inclination angle on mud weight window was studied by Yew and Liu (1992). Their analysis illustrated that wellbore stability is very sensitive to pore pressure, and the mud weight window has an inverse relationship with the inclination angle. Fuh et al. (1998) presented a case study for designing a high-angle hole to determine pore pressure. Their results showed that selection of safe mud weight should be based on the inclination angle, in-situ stress, pore pressure and rock strength. Awal et al. (2001) utilized an analytical method based on poroelastic model to optimize the wellbore trajectory. Manshad et al. (2014) examined four rock failure criteria, namely the Mohr–Coulomb, Mogi–Coulomb, modified Lade and Tresca yield criteria, and applied them to determining the optimum drilling direction and mud pressure. The results showed that the estimated minimum mud pressure required (MMPR) of Mohr–Coulomb and Tresca criteria is higher than that of the Mogi–Coulomb and the modified Lade criteria.

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Zare-Reisabadi et al. (2012) introduced an analytical model that estimates the optimum well trajectory as well as mud pressure in borehole stability analysis during drilling by using the Mogi–Coulomb failure criterion. The results demonstrated that in different in-situ stress regions, trajectory has a significant role in wellbore stability.

On the other hand, numerical analysis has been also used to study the wellbore stability. Zervos et al. (1998) used finite element model for rock elastoplastic behavior to calculate the optimum mud pressure. Results confirmed that the difference in mud pressure predictions between elasticity and plasticity depends strongly on the employed failure criteria.

Salehi et al. (2007) utilized wellbore stability in under-balanced drilling with respect to equivalent circulating density with an elastoplastic model. Manriquez et al. (2008) applied finite element method to studying the complex problem of stability of multi-branch horizontal open holes in drilling, completion, and production conditions. They concluded that the lateral wells are the most unstable region. Muller et al. (2009) used a finite element program that considers coupled fluid-mechanical effects and elastoplastic behavior of rock for analyzing stability of wellbore.

Wang and Sterling (2007) developed an efficient numerical strategy, based on finite element method, to estimate the safe range of drilling pressures for various site conditions, and also to develop a quantitative understanding about the role of a filter cake in borehole stability. Hawkes et al. (2002) applied normalized yielded zone area (NYZA) to modeling of borehole instability and multiphase flow.

In this work, NYZA was used for indication of wellbore instability risk. NYZA is the cross-sectional area of the yielded zone around the well divided by the initial area of the well. Experience has shown that the beginning of borehole instability problems is often associated with NYZAs greater than 1 (McLellan and Wang, 1994; Hawkes and McLellan, 1997; McLellan et al., 2000). Goshtasbi et al. (2013) used NYZA to determine the optimum mud pressure in multi-lateral well. They showed that the required mud pressure for the junction stability is much larger than those for the lateral branch and the main wellbore in each stress regime.

Abrasiveness index and penetration rate are very important factors for economic excavation. Tripathy et al. (2015) presented a prediction method to determine the Cerchar abrasiveness index and penetration rate related to rock excavation using simple geomechanical parameters. It was shown that the prediction capability of artificial neural network (ANN) was better than that of multiple linear regression analysis (MVRA) when using other geomechanical parameters as predictors.

Uniaxial compressive and shear strengths are required in initial stage of design of rock engineering. Singh et al. (2017) have presented a method to predict compressive and shear strengths. Simple and easily determined parameters such as point load index, tensile strength, unit weight and ultrasonic velocity were considered as inputs, and compressive and shear strengths were applied as outputs. ANN was applied to predicting strength parameters. Analysis showed that ANN has the better reliability than regression method, but only for rocks under low confinement and free of moisture.

Due to substantial challenge in full-scale numerical analysis of wellbore stability to address competing objectives such as improved performance and reduced processing time, a novel algorithm has been used to solve the problem of wellbore instability.

2. Problem definition and proposed methodology

As mentioned above, preventing wellbore instability is one of the main concerns in well trajectory design in petroleum field. In this study, a novel algorithm was suggested to find the best well trajectory in wellbore stability analysis. FLAC3D software was utilized to carry out the stability analyses. For validation of the method, an analytical method based on elastic solution was applied to comparing the results. Due to the time-consuming process of optimization, we tried to develop a proxy model to describe the behavior of actual wellbore simulator. If a limited number of simulations can be performed on the simulator (FLAC3D numerical code) and provide a high coefficient of determination for the proxy, the simulator can be replaced by this proxy model. Nonlinear state and complicated process are other problems in optimization process. Sometimes, using an analytical method could not find the best solution. In these cases, conducting an intelligent method with application of feedback control may be useful. The proposed algorithm in this paper covers the mentioned problems.

The flowchart of genetic algorithm (GA)-proxy-feedback control algorithm for the global minimum mud pressure required (GMMPR) determination is shown in Fig. 1. In Fig. 1a, a group of azimuth and inclination angle has been selected and MMPR for these samples has been calculated using a feedback control algorithm. To build a proxy model, input variables consisting of azimuth, inclination angle and mud weight, and NYZA as the output variable have been proposed till the coefficient of determination of proxy is not satisfied, then a new sample is selected and added to other samples to build a convenient proxy model.

In Fig. 1b, GA in association with feedback control algorithm has been used to find the optimum well trajectory. As illustrated in this figure, the proxy model is applied to wellbore stability analysis instead of FLAC3D numerical code. In the following, major steps of the proposed methodology will be explained.

3. Wellbore stability based on elastic assumption

To identify the effective stresses around the wellbore and learn about the failure of wellbore, modeling the stresses at the borehole is one of the most commonly used methodologies. Aadnøy and Looyeh (2011) applied analytical methods to obtain the stress state at the directional wellbores using in-situ principal stresses. When a borehole is drilled to create a space in rock mass, stress is transmitted to wellbore wall, leading to stress concentration. This concentration can be calculated utilizing a common procedure.

In the following, the elastic solution procedure will be presented:

$$\sigma_x = \left(S_H \cos^2\alpha + S_h \sin^2\alpha\right)\cos^2 i + S_v \sin^2 i \quad (1)$$

$$\sigma_y = S_H \sin^2\alpha + S_h \cos^2\alpha \quad (2)$$

$$\sigma_{zz} = \left(S_H \cos^2\alpha + S_h \sin^2\alpha\right)\sin^2 i + S_v \cos^2 i \quad (3)$$

$$\sigma_{xy} = 0.5(S_h - S_H)\sin(2\alpha)\cos i \quad (4)$$

$$\sigma_{yz} = 0.5(S_h - S_H)\sin(2\alpha)\sin i \quad (5)$$

$$\sigma_{xz} = 0.5\left(S_H \cos^2\alpha + S_h \sin^2\alpha - \sigma_v\right)\sin(2i) \quad (6)$$

where σ_x, σ_y, σ_{zz}, σ_{xy}, σ_{xz}, and σ_{yz} are the transformed stress components (see Fig. 2); S_v, S_H and S_h are the vertical, maximum and minimum horizontal stresses, respectively; α is the wellbore