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An analytical model of coal wellbore stability based on block limit equilibrium considering irregular distribution of cleats

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ABSTRACT

An analytical model of coal wellbore stability is established based on the block limit equilibrium method, taking the irregular distribution of cleats into account. Because coal seam is cut into discontinuous blocks with different shapes and sizes, block slip can be treated as the symbol of coal wellbore instability. According to the geometric characteristic of blocks, blocks surrounding the wellbore can be divided into 3 categorizes: type I, type II and type III. To evaluate the block slip, the stress distribution near the wellbore is determined based on the continuous medium mechanics and the fracture mechanics. Using Mohr–Coulomb criterion and limit equilibrium method, the critical conditions of block slip are derived by defining the failure coefficient, including type I, type II and type III. The proposed model is verified by comparison of the obtained results from the proposed analytical method with the discrete element method as well as the actual drilling. It can be proved that the proposed model can predict accurately block slip. Additionally, the effect of drilling fluid pressures on the wellbore stability is specially investigated. The results show that with the increasing of drilling fluid pressure, the degree of wellbore collapse may be more severe. Meanwhile, the analysis method of reasonable drilling fluid pressure for coal drilling is proposed based on the interval theory, combining the slip area of blocks. Finally, the parametric study is focused on investigating the effects of the internal friction angle of face cleats, the cohesion of face cleats and the tensile strength of butt cleats on the failure coefficients of blocks.

1. Introduction

Coal-bed methane is an important energy supplement for world's natural gas requirements. However, coal wellbore instability is still one of the major problems encountered during drilling, due to the special properties of coal seams, such as developed natural cleats, low tensile strengths, low elastic modulus, anisotropy of mechanical properties (Gentzis et al., 2009a; Keim et al., 2011; Huang et al., 2013). For coal seam, block slip along cleats can be treated as one of the most important failure modes of wellbore stability (Aoki et al., 1994; Last et al., 1995; Chen et al., 1998; Okland and Cook, 1998; Chen et al., 2003; Tan et al., 2005). After the stresses acting on cleats satisfy the specified failure criterion, blocks slide into the borehole along the cleats. Compared to wellbore stability of the conventional sandstone, the most significant difference of coal wellbore stability is that an increase of drilling fluid pressure maybe has a negative effect on wellbore stability (Santarelli et al., 1992a; Chen et al., 2003; Tan et al., 2005) according to the field experience. Note that, the reason that results in the phenomenon has not been fully understood.

Up to now, two category approaches have been proposed to analyze wellbore stability, mainly focusing on numerical analysis methods and analytical methods. Chen et al. (2002) proposed a numerical model to discuss the effect of drilling fluid infiltration into formation on wellbore stability. Yamamoto et al. (2002) proposed a numerical model of wellbore stability, where surrounding rock was modeled as the continuum model with a crack. Chen et al. (2003) carried on a numerical analysis of wellbore stability considering the effect of drilling fluid infiltration into formation. Tan et al. (2005) developed a numerical approach to model the effect of a combination of several parameters on wellbore stability, including fractures, fracture strength reduction and drilling fluid infiltration. Whittles et al. (2007) established a series of plane strain models to predict the wellbore stability using FLAC program. Hawkes (2007) established the elastic and elastoplastic models to investigate the effects of rock strength and buried depth on the wellbore stability. Deisman et al. (2008) discussed the effect of cleats on coal strength by the Hoek–Brown criterion and the geological strength index. Gentzis (2009) and Gentzis et al. (2009b) analyzed wellbore stability by numerical codes, taking the effects of weak planes and well trajectories into account. Deisman et al. (2010) performed a series of numerical models to analyze the impact of cleats on coal strength. Qu and Shen (2010) and Qu et al. (2011a, b) established the model of coal wellbore stability using the discrete element method. Li et al. (2012) established a numerical analysis model of wellbore stability for shale reservoirs. Zhao et al. (2013) established a finite element model to simulate wellbore collapse of shale considering the effect of fractures. Park and Min (2013) develop a discrete element model of wellbore

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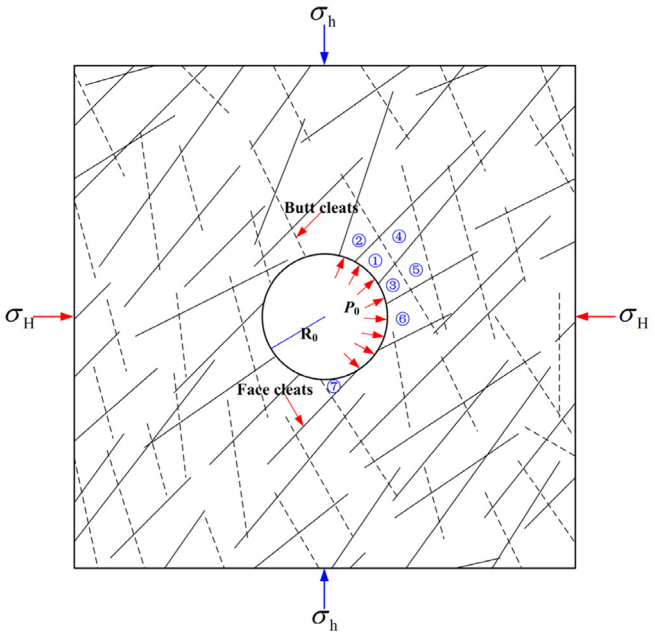

Fig. 1. Analysis model of coal wellbore stability considering irregular pattern of cleats.

stability considering the existing of weak planes. Additionally, Santarelli et al. (1992b); Zhang et al. (1999, 2003); Zhang and Roegiers (2000, 2005); Pine et al. (2006) and Yan et al. (2013) developed the corresponding numerical analysis models of wellbore stability in the fractured formation, respectively. Using numerical analysis methods, an exact solution of wellbore instability can be obtained. Nevertheless, the numerical analysis brings the calculation process rather demanding.

Though pioneering researchers have made great progresses for wellbore instability using numerical analysis methods, analytical approaches still have some advantages in some aspects, especially as a basis to promote the development of numerical analysis methods. Compared to numerical analysis models, analytical models used to analyze coal wellbore stability are relatively few. Zhao et al. (2012) proposed an analysis model to determine the effects of geometric and mechanical properties of cleats on the wellbore stability. Zhang (2013) proposed an analysis method of wellbore stability by defining a slip failure gradient, considering weak bedding planes. Zhu et al. (2014) proposed an analytical model to analyze the effect of geometric properties of cleats on coal wellbore stability. Cui et al. (2014) developed a real-time model of coal wellbore stability for underbalanced drilling, considering the effect of cleats. In spite of improvements, analytical models above still have a number of shortcomings, especially:

(1) The cleat distribution of wellbore stability models proposed is very regular, which is different from the actual distribution of cleats. In order to obtain more accurate predictions, the irregular distribution of cleats should be fully considered in the wellbore stability analysis.
(2) Of analytical models above, the stress induced by cleats existed is not considered, which maybe leads to the prediction results that differ with the actual results. To improve the prediction accuracy, the induced stress by cleats should be considered in analytical models of wellbore stability.
(3) In the works by Zhao et al. (2012), Zhu et al. (2014) and Cui et al. (2014), it is assumed that wellbore instability is only dominated by the radial equilibrium of matrix blocks, neglecting the shear failure along cleat surfaces (i.e. assuming that the shear failure along cleat surfaces has occurred), which maybe leads to inaccurate predictions. Therefore, to predict accurately wellbore instability, the shear failure along cleat surfaces should be evaluated.

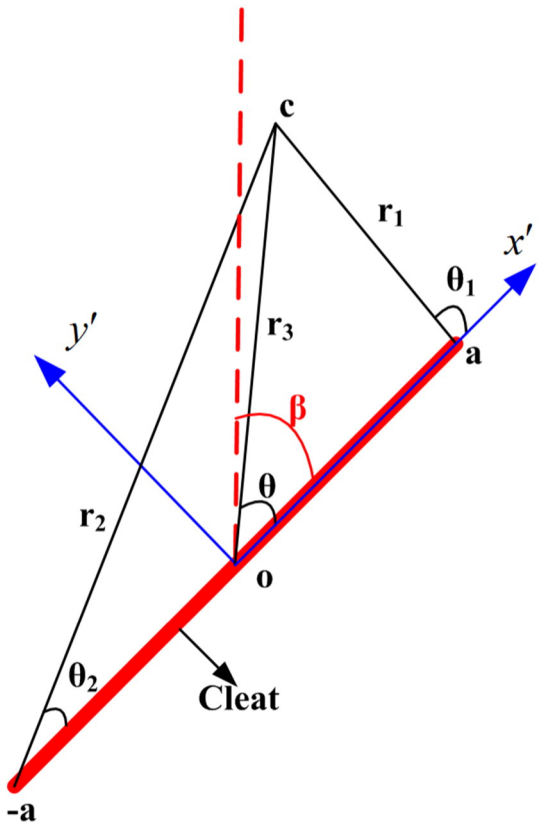

Fig. 2. Stress analysis under the single cleat.

(4) The verification of the analytical method is neglected, i.e. the comparison of results of the analytical method with numerical analysis method is not performed.

Although important improvements have been achieved in the analytical models above, the mechanism of coal wellbore instability is still not fully understood under irregular distribution of cleats. In this paper, an analytical model of coal wellbore stability is established based on the block equilibrium method, taking irregular distribution of cleats into account. In order to verify the proposed model, the

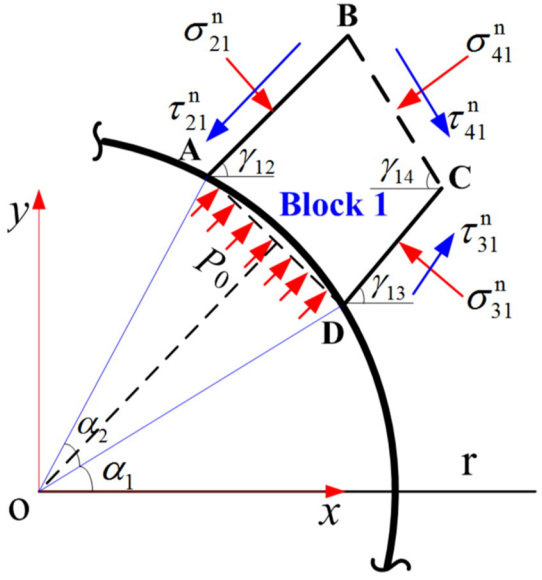

Fig. 3. Analysis model of block type I.