Journal of Petroleum Science and Engineering 139 (2016) 94–103

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Study on effect of in-situ stress ratio and discontinuities orientation on borehole stability in heavily fractured rocks using discrete element method

Ehtesham Karatela [a,*], Abbas Taheri [a], Chaoshui Xu [a], Gregor Stevenson [b]

[a] Deep Exploration Technologies Cooperative Research Centre, School of Civil, Environmental and Mining Engineering, The University of Adelaide, Adelaide, Australia
[b] BHP Billiton, Australia

ARTICLE INFO

Article history:
Received 20 July 2015
Received in revised form
16 November 2015
Accepted 15 December 2015
Available online 17 December 2015

Keywords:
Borehole stability
Discrete element model
Numerical simulation
Fracture

ABSTRACT

Borehole instabilities pose significant challenges in drilling and completion operations, specifically in the areas where pre-existing fractures are intersected by the borehole. In-situ stresses play a vital role in failure mechanism around an excavation. In addition, discontinuities increase the probability of instability. Therefore analyses of effect of in-situ stress in discontinuous media have significant importance in identifying efficient drilling methodologies. Numerical investigation on the behaviour of an unsupported vertical cylindrical borehole in heavily fractured rock mass is presented in this study. Discrete Element Model (DEM) based code Universal Distinct Element Code (UDEC) is used as the simulation tool. With taking into account the in-situ stress conditions in Cooper basin, South Australia, an unsupported borehole of 0.15 m radius in the centre of the model was simulated comprising of two fracture sets. The vertical stress applied correlates with the 1.5 km depth of the Cooper basin. The effect of fracture orientation and in-situ horizontal stress ratio (σ_H/σ_h) on the stability of the rock mass around the borehole was investigated. It has been shown that the induced stresses due to excavation lead to the development of a yielded zone around the borehole. Borehole stability criteria relevant to the extent of yielded zone and maximum displacement around the borehole were introduced into stability analysis. Results show that when the in-situ stress ratio increases the rock blocks at borehole wall tend to move towards the centre of borehole, consequently yielded zone around the borehole increases. Similarly, the fracture orientation changes the angle of borehole fracture intersection which aids in displacement increase as well as the location of block detachment. Furthermore the change in fracture orientation highly influences the formation of yielded zone.

1. Introduction

Borehole stability is considered to be one of the most important problems in the drilling process. The deformations, breakouts and drilling induced failure can have significant consequences and may lead to well collapse. A lack of accurate wellbore stability analysis can bring up problems like washouts, breakout, borehole collapse, stuck pipe and mud loss (Peng and Zhang, 2007). Instability problems also add up to 10% of total drill time (Li et al., 2012) and may lead to abandoning the well. Extensive studies have been carried out for borehole instability, including analytical, experimental and few numerical studies. Fig. 1 demonstrates that when the mud pressure is higher than the formation pressure or pore pressure, the wellbore may experience ballooning and washout. Similarly it can be observed in Fig. 1 that when the mud weight is less than the shear failure gradient, the borehole experiences shear failure (Bell and Gough, 1979; Zoback et al., 1985; Tingay et al., 2005; Zoback, 2007). According to Fig. 1, one of the most important mechanical borehole stability problems is shear failure due to underbalanced drilling conditions.

Rock failure can occur as a result of rock strength anisotropy caused by weak bedding planes and natural fractures. In these cases increased mud weight can further deteriorate the situation by mud loss (Santarelli et al., 1992). Modelling of such a geologic environment presents many challenges and requires coupling the in-situ stress, pore pressure, mud weight and fracture properties.

Whereas borehole stability in continuous media has been extensively studied, little attention has been paid to what happens in the case of fractured and interbedded formations. Recent field observations have shown that despite their relatively small

* Corresponding author.
E-mail address: ehtesham.karatela@adelaide.edu.au (E. Karatela).

http://dx.doi.org/10.1016/j.petrol.2015.12.016
0920-4105/

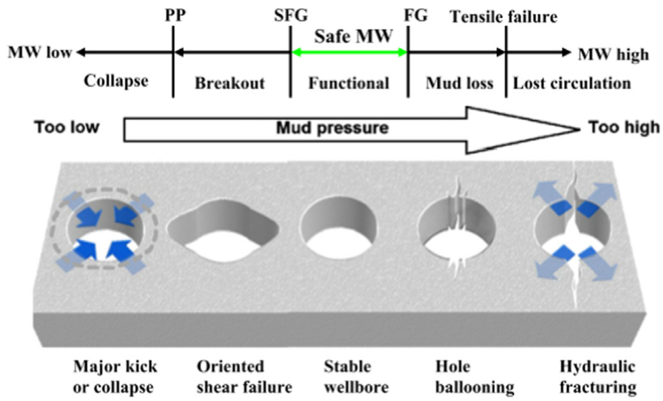

Fig. 1. Schematic relationship of wellbore failure (Zhang, 2013).

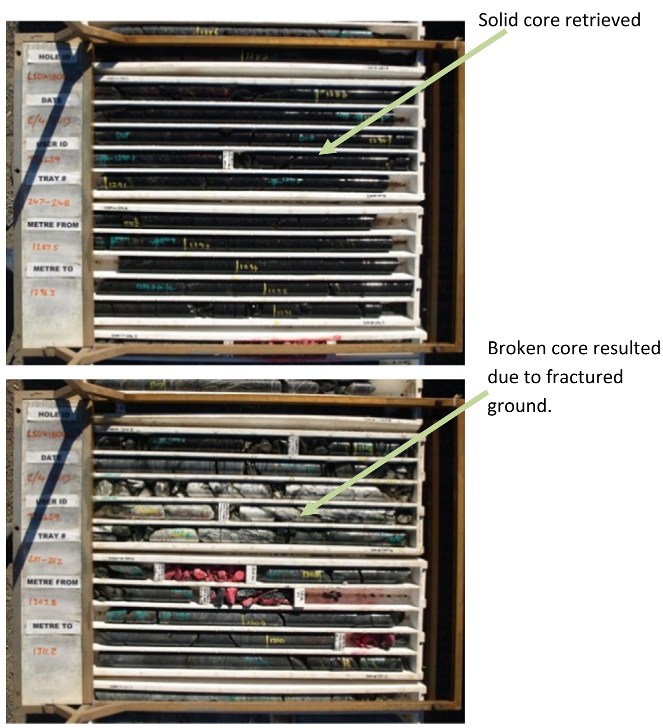

Fig. 2. Core retrieved from the borehole from 1207 to 1311 m at a mining exploration site in Western Australia.

diameters, boreholes can severely be affected by layering and the presence of natural fractures in the rock mass. Structurally controlled failures are the most common wellbore instability problems. For example, BHP Billiton drilled holes ranging from 800 to 2200 m depths in Mount Keith mine which is an open pit nickel mine in Western Australia. In this project it was experienced that, the general nature of the discontinuous ground condition makes the drilling process challenging. Similarly, Fig. 2 shows the pictures of core retrieved from a borehole at a mining exploration site in Western Australia at depth of 1287–1311 m operated by BHP Billiton. The core attained is from hard felsic and sheared puggy ultra-mafic zones. It can be observed in the Fig. 2 that as soon as the fractured ground is encountered core recovery is compromised.

Various methods have been used to analyse the problem of borehole stability and to explain the mechanisms involved with borehole collapse (Adams, 1912; Plumb and Hickman, 1985; Aadony, 1988; McLean and Addis, 1990; Santarelli et al., 1992; Ewy, 1998; Okland and Cook, 1998; Zhang et al., 1999; McLellan et al., 2000; Zhang and Roegiers, 2000; Haimson, 2001; Chen et al., 2002, 2003; Yamamoto et al., 2002; Moos et al., 2003; Haimson and Lee, 2004; Al-Ajmi, 2006; Fjaer et al., 2008; Kang et al., 2009; Ottesen, 2010; Salehi et al., 2010). However, the problem of borehole instability remains unsolved for the boreholes drilled in problematic situations such as unconsolidated formations, faulted and fractured rocks and salt domes. In a borehole intersecting fractured rock medium, borehole collapse has been explained by invasion of mud into the fractures. The invasion of mud increases the pore pressure therefore reducing the effective normal stress. A shear release then results in lateral displacement at the fracture plane. However, in underbalanced conditions where mud invasion is unlikely, predominant failure mechanisms are induced by stress concentration. Therefore, more sophisticated studies are required to devise a strategy to reach targeted depth safely.

Recently numerical methods have been utilized to understand the problem of borehole instability (Yamamoto et al., 2002; Zhang and Roegiers, 2002, 2005; Salehi et al., 2010; Hu et al., 2012). Continuum based, Finite Element Model (FEM) is commonly used by many researchers. However, FEM is unable to simulate the fracture nature of rock mass around borehole in heavily fractured condition (Jing, 2003). In order to model a medium with greater number of discontinuities DEM is assumed to be more appropriate to simulate rock behaviour (Jing, 2003).

One of the earliest works of borehole stability using numerical analysis in fractured rocks was carried out by Santarelli et al. (1992). These authors applied discrete element method (DEM) to the drilling data obtained from a problematic drilling site comprising of heavily fractured basalt and Tuff. They used conventional method of increasing mud weight to stabilize the well. Consequently, they concluded that high mud weights can increase the formation damage by penetrating into the fractures. Similarly, Yamamoto et al. (2002) presented a study of deviated borehole to understand the mode of failure on a weak plane. They concluded that penetration of fluid caused the fracture to slide and the severity increases with changing stress conditions. However, these numerical studies did not investigate the plastic deformation around the borehole induced by stress concentration.

This paper aims to investigate the effects of discontinuities orientation and in-situ horizontal stress ratio on borehole instability in heavily fractured condition taking into account in-situ stress conditions of Cooper basin in Australia. A series of numerical analysis on a borehole drilled in fractured rock mass are conducted using two dimensional discrete element method (DEM) code UDEC (Universal Distinct Element Code).

2. In-situ stress state in Cooper basin

Cooper basin is Australia's most prolific onshore basin where hydraulic fracturing treatments are reportedly being problematic. More than 3000 exploration and production boreholes have been drilled in the Cooper basin. One of the problems to achieve the targeted drilling depth is the orientation and magnitude of maximum horizontal stress (σ_H) in the Cooper basin. Details on tectonic evolution of the Cooper basin are discussed by Apak et al. (1997). The reader is directed to this study for in depth details of geological and tectonic evolution of the basin. The interaction of in-situ stresses with the pre-existing fractures and faults have been investigated by Reynolds et al. (2005) and Nelson et al., (2007) to understand the fracture propagation and permeability. Boreholes drilled intersected various natural fractures which were observed on the image logs (Nelson et al., 2007). Additionally few studies have investigated the distribution and density of fractures within the area of Cooper basin (Backé et al., 2011; Abul Khair et al., 2012). However, borehole stability has not been deeply investigated in this area. In particular the effect of different in-situ stress ratios and their interaction with fracture orientation has not