Journal of Petroleum Science and Engineering 133 (2015) 507–517

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Performance, simulation and field application modeling of rollercone bits

Behrad Rashidi*, Geir Hareland[1], Zebing Wu

Department of Chemical & Petroleum Engineering, University of Calgary, Calgary, Alberta, Canada T2N 1N4

ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form
23 May 2015
Accepted 2 June 2015
Available online 20 June 2015

Keywords:
Rollercone bit
Rate of penetration
Rock confined/unconfined compressive strength
Weight on bit
Bit revolution per minute
Cutter wedge angle
Rock failure angle
Bit performance/simulation studies
Bit wear coefficient

ABSTRACT

Drilling simulation technology has been used extensively to optimize drilling operations so as to minimize the associated costs and risks. Optimum bit types and designs with corresponding drilling parameters can be recommended utilizing a simulator with rate of penetration (*ROP*) models. There have been several attempts to develop *ROP* models that can deliver the most reliable outputs, required for the pre-planning and post analysis applications, using various sets of drilling parameters. However, due to the existing modeling complexities, these attempts have not been successful. In this study, a new *ROP* model is developed for the rollercone bits, which properly integrates the effect of main drilling parameters as well as cutting structure of the bit. The model is mathematically derived based on the mechanism of single cutter–rock interaction, and calibrated utilizing sets of full scale laboratory data. Also, the bit wear effect for simulating accurate rock strength and *ROP* values is included in the analysis using a previously published model. One of the most important features of the newly introduced *ROP* model is that it can be easily inverted to generate accurate rock strength values using offset and/or real-time field data. This unique characteristic of the *ROP* model makes it a valuable candidate for drilling simulation studies to optimize drilling operations in the most cost effective manner. The verification of the introduced *ROP* model is performed through series of simulation analysis and comparing the generated rock strength logs to the outputs of a commercially available drilling simulator. The comparison of the results obtained from the simulator and the *ROP* model as well as field data has been quite encouraging which signifies the application of the developed model in determining the best case scenario for planning and/or drilling of future wells with lowest possible expenditures.

1. Introduction

In oil and gas industry, it has been well recognized that the associated time and cost of drilling wells is a major part of the total field development expenses. One of the main objectives of the entire well development plans is to minimize the overall well cost in compliance with safe operations and environmental regulations. Drilling rate is one of the key parameters in optimizing the performance of the operations through reducing the rotating time of the bit. Accordingly, drilling rate models play an important role in improving drilling performance using available offset well data and/or in real-time drilling.

Extensive studies have been performed to develop comprehensive *ROP* models for the commonly used rollercone bits considering the effect of associated drilling and bit design parameters. However, due to the existing modeling restrictions, as outlined below, previous attempts have not been successful and never led to develop a practical model.

- Mathematically modeling forces applied to the formation by bit cutters.
- Mathematically modeling generated rock volume by each single cutter as well as estimating cumulative generated cutting volume considering bit rotation.
- Taking into account integrated effect of operational and bit design parameters.
- Developing invertible *ROP* models that can be used to estimate formation strength values using any sets of drilling parameters.

Therefore, the developed *ROP* models that integrate the above-mentioned parameters/effects can be utilized as the core engine of

* Corresponding author.
E-mail addresses: behrad.rashidi@hotmail.com (B. Rashidi), geir.hareland@okstate.edu (G. Hareland), zbawu@ucalgary.ca (Z. Wu).
[1] Currently: Chemical Engineering Department, Oklahoma State University, Stillwater, OK 74075-5020, United States.

http://dx.doi.org/10.1016/j.petrol.2015.06.003

drilling simulators for conducting drilling optimization studies. Available offset well data can be used as the input to drilling simulators in order to generate apparent rock strength logs (ARSL) and/or formation drillability over the well interval. Rock strength logs can also be generated with a good accuracy using log data. The trends obtained from log data could be useful in verifying correct rock strength variations generated by the *ROP* models specially when sufficient drilling offset information is not accessible.

The main goal of conducting drilling simulation studies is to achieve lowest cost of the well through optimization analysis that includes recommending optimum sets of bit types, designs as well as corresponding operational parameters and bit pull depths while minimizing drilling problems (Nygaard et al., 2002). Also, real-time transmission and analysis of drilling data, from a remote server to an office location, plays an important role in optimizing drilling operations. Drilling engineers can provide expert opinions to rig personnel, thus increasing drilling efficiency as well as reducing the associated risks (Rashidi et al., 2010).

The primary objective of this study is to develop a new, comprehensive and practically applicable *ROP* model for application use in a simulator environment for drilling simulation studies, pre-planning, real-time and post analysis operational mode utilizing rollercone bits.

2. Overview and background

2.1. Single cutter–rock interaction

The cutter–rock interaction is the preliminary area of study in analyzing drilling performance of rollercone drill bits. There exist several shortcomings to this area which is mainly due to the complexity in rock failure phenomenon as well as modeling the contact forces during digging action of the bit cutters.

Several models have been introduced to investigate rock breakage angle of the rock chips using a force balance system. Hill et al. (1947) and Outamans (1960) introduced their rock breakage models for ductile materials which could not be applied in brittle materials with much accuracy. Paul and Sikarskie (1965) proposed a theoretical study for a static wedge penetration model based on Mohr-Coulomb failure criterion. Their theory expressed rock failure mechanism through crushing and chipping phases as shown in Fig. 1. The positive slope lines represent the elastic deformation or crushing phases whereas chip formations are characterized by the negative slope lines in each cycle. Dutta (1972) put forth a theory explaining rock breakage phenomenon as a momentarily release of strain energy including both crushing and chipping events. It has been then shown that the rock breakage phenomenon can be considered as a brittle failure characterized by fractures as a result of cutter's indentation. Cheatham (1985) conducted a study on the amount of force required for a wedge shaped cutter to penetrate into the rock. In his model, the rock underneath cutters was assumed to be isotropic and homogeneous in a rigid plastic state which satisfies yield condition in Mohr–Coulomb theory of failure. The process of rock failure under indentation of cutters includes build-up of the stress field, formation of a zone of inelastic deformation and development of a crater respectively.

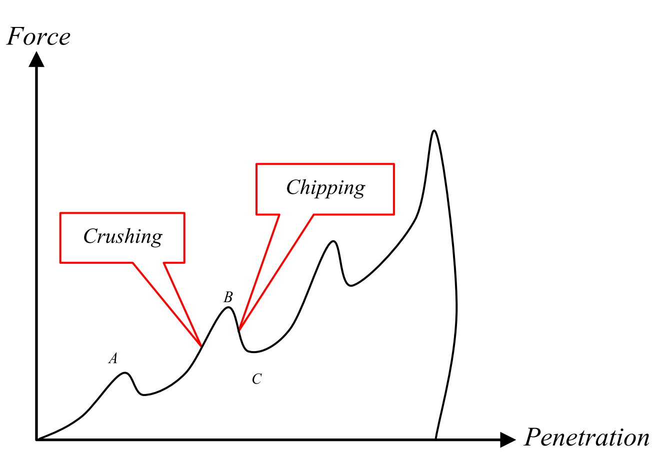

Fig. 1. Schematic representation of experimental cutter force to rock penetration.

2.2. Rollercone bit modeling

Several drilling models have been introduced over the years to express rock-bit interaction of rollercone bits as a function of associated drilling and bit design parameters. Primary models were published by Galle and Woods (1960) and Morlarn (1961) in soft formations introduced *ROP* models merely as a function of *WOB* and *RPM*. Maurer (1962) proposed his model as a function of operating parameters and rock strength but it failed to predict *ROP* response to the applied low *WOB*. Bingham (1965) suggested a new *ROP* model based on limited laboratory data with the assumption of negligible threshold weight on bit (WOB_0) and rotary speed exponent of one despite the fact that *ROP* response to increasing rotary speed diminishes at high *RPM* values. Few years later, Bourgoyne and Young (1973) suggested a drilling rate model considering the effect of several drilling variables on *ROP*. This model was derived merely for unsealed roller bearing milled tooth bits in vertical wells and the effect of parameters such as *WOB*, *RPM*, bit tooth wear and others were assumed to be independent of one another (Ettehadi, 2007). In 1981, Warren introduced a new *ROP* model that integrated the effects of the mechanical and lithological parameters. The model was developed using dimensional analysis and generalized response curves for the best fit using laboratory data. The results have revealed that generated rock volume by a single tooth is proportional to the tooth force squared and inversely proportional to the rock strength squared. His model was later modified by Rampersad et al. (1994) for taking into account bit wear and chip hold down effects. Although the predicted *ROP* values match field and laboratory data using this model, it is not always possible to obtain positive rock strength values utilizing the inverted model. In 1995, Ma developed a computer simulation program based on rock-bit interaction which reflected the effect of cutters structure on *ROP*. This model did not integrate the effect of rotary speed variations in simulating *ROP* values and is also very complex and time consuming to run, so it could not be used in drilling simulation studies especially in real-time analysis.

3. Technical approach

3.1. Rollercone bit performance modeling

Development of a new, accurate and applicable drilling rate model for rollercone bits is one of the keys to get valuable outcomes from drilling simulation studies. The model should have the capability of directly estimating *ROP* as well as approximating rock strength values utilizing the inverted model with known parameters. Furthermore, the model should properly reflect the effect of changes in bit design and cutters' geometry for various bit IADC codes.

In this study, a new comprehensive and practical *ROP* model for rollercone bits is developed based on the approach introduced by Evans and Murrel (1962) and further modified by Ma et al. (1995). A single cutter performance model was first established based on the experimental data and the *ROP* model was then introduced by