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Research and application of reaming subsidence control in horizontal directional drilling

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ABSTRACT

In the reaming operation of horizontal directional drilling, a centralizer is often attached to a reaming-bottomhole assembly (R-BHA) to change the reamer side force. This can address the problem of large-diameter reamer subsidence. However, there is no scientific basis for how to attach the centralizer in the R-BHA. In this paper, an equation for the reamer side force in a two-centralizer R-BHA is derived, based on three moment equations. Then, using the Drucker-Prager criterion as a rock constitutive relation and the shear criterion for predicting damage initiation, a nonlinear dynamic finite element model is established using the finite element method (FEM). In addition, the trajectory of the reamer and the failure of the drilling tools are analyzed. The study results show that the combination of the analytical and finite element methods can effectively improve the installation accuracy of the centralizer. The attachment range of the centralizer can be quickly determined by a simple calculation of the analytical method, and the FEM (with high computational precision) can be used to analyze the subsidence control capacity of the R-BHA in detail. Application to a field case demonstrates the feasibility of the method, and the study conclusions provide a scientific basis for the centralizer attached to the R-BHA, which is important for controlling reaming subsidence.

1. Introduction

Horizontal directional drilling (HDD) is a trenchless construction method typically used for pipeline construction in petroleum and natural gas industries (Ariaratnam et al., 2010; Ibeh and Nnakaihe, 2016; Lubrecht, 2012; Sarireh et al., 2012). It has lower economic costs, takes less time to complete, is environmentally friendly and has a high efficiency compared with other construction methods. The HDD process is typically completed in three distinct steps: (1) to drill a pilot bore with a drill bit, (2) to subsequently enlarge the pilot bore with a larger diameter reamer and (3) to pull back the product pipe. In these three steps, the quality and efficiency of the reaming operation determine whether the construction project can be completed successfully.

In recent years, with the development of the global economy and the increase in energy demand, the diameters of oil and gas pipeline constructions are becoming larger; for example, the pipe diameter in the trans-Asia gas pipeline is 1422 mm. The increase in pipe diameter results in an increase in the number of reaming stages, and the effects of gravity on the reamer and the drill pipe can cause serious reamer subsidence in the reaming operation. This may produce irregular borehole shapes such as those shown in Fig. 1 (Liu et al., 2014). These irregular shapes can cause borehole collapse and sticking accidents, and may even cause failure of the whole construction process.

According to analysis (Ariaratnam et al., 2015; Lan et al., 2011; Lueke and Ariaratnam, 2006; Shu and Ma, 2016), the factors that affect reaming quality include crossing strata, reaming stages, reaming diameter, mud properties and the reaming-bottomhole assembly (R-BHA; a drill assembly with reamer for reaming operations). Under the premise that geological conditions and reaming conditions cannot be changed, using a well-designed R-BHA becomes the main method for controlling reaming subsidence (subsidence behavior of the reamer during the reaming operation). In general, two centralizers are attached to the R-BHA to enhance the resistance to reaming subsidence, but mechanical analysis and control capability of subsidence have not been systematically studied in detail. Most of the existing R-BHA designs are based on field experience, and it is not clear if they are of the best design possible.

Changing the bottomhole assembly (BHA) to control hole deviation was studied in oil drilling as far back as in the 1950s. Lubinski and Woods (1955) suggested that using a centralizer could increase the weight on bit without increasing the deviation of the well, and differential equations for the force and deformation of the drill string were derived. In addition, the theoretical analysis results were made into a chart and were widely used in practical drilling. Subsequently, Speer

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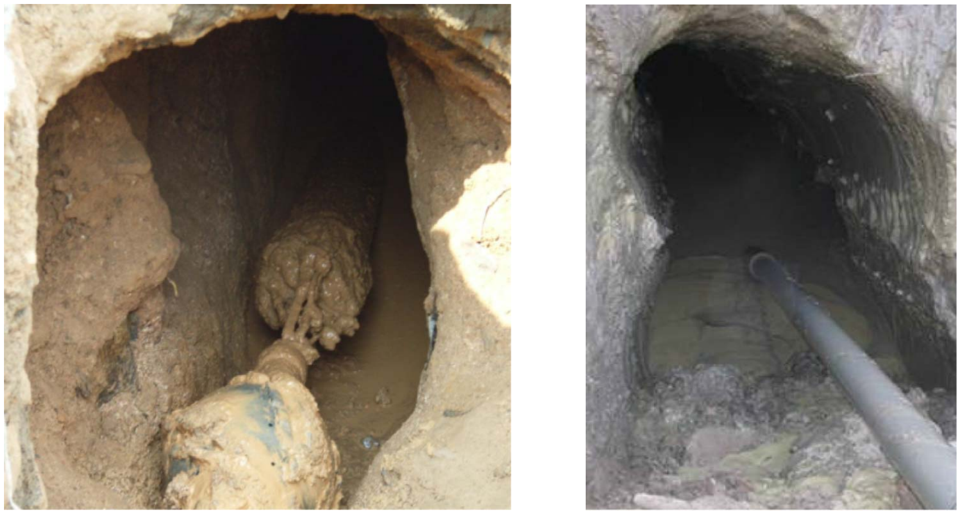

(a) Gourd-shaped hole (b) Pear-shaped hole

Fig. 1. Shape of the reaming borehole.

and Holiday (1955) thought that the rational use of a centralizer could control the spacing of the curved boreholes, and that utilizing multiple centralizers could reduce the growth rate of the borehole inclination. Hoch (1962) and Wiley (1965) proved that a near-bit centralizer could reduce the bit lateral displacement. Based on three moment equations, an analytical model of the bit side force was deduced by Bai (1982). Dogay et al. (2009) put together the basic concepts of mechanics on a drill string to find a simple and economical way for drilling directional wells, and the force of a slick BHA and a single stabilizer BHA were analyzed. The potential energy principle, the energy method and the finite difference method (Agawani et al., 1994; Mahyari et al., 2010; Walker, 1973; Yang et al., 2008) were also used to analyze the BHA, to ensure that the drilling was in accordance with the designed borehole trajectory.

The finite element method (FEM) has also been used to analyze BHA. Millheim et al. (1978) and Millheim and Apostal (1981) studied the influence of BHA on the bit trajectory using the FEM. Akgun (1999, 2004) analyzed the influence of a centralizer on the bit side force and tilt. Jafari et al. (2011) found that transverse and longitudinal vibrations were the main causes of BHA failure, and the placement of a centralizer was explained. Zhu et al. (2014, 2016) have recently established a nonlinear dynamic finite element model, composed of a cone reamer entity and a three-dimensional rock, and have studied the effect of a near-reamer centralizer on the vibration reduction of a reamer in soft and hard sandwiches. The structural parameters of the centralizer were also given.

The studies mentioned above were conducted based on rock drilling at a depth of several kilometers. In addition, most of these drillings were designed for vertical or highly deviated wells. In contrast, HDD is a horizontal drilling technique with a longer crossing distance and a larger diameter borehole, for which heavy drilling tools need to be used. Although BHA have been studied systematically in oil drilling fields, it is unreasonable to use the conclusions from these systematic studies to address HDD reaming subsidence. Therefore, the dynamics mechanism and the control of HDD reaming subsidence remain unclear. To study subsidence control in HDD reaming, we derive an equation for the reamer side force of a two-centralizer R-BHA based on three moment equations, and then establish a nonlinear dynamic finite element model using the FEM, with the Drucker-Prager criterion as the rock constitutive relation and the shear criterion for predicting damage initiation. Finally, combining the advantages of these two methods, we determine the influence of the two-centralizer R-BHA on reaming subsidence, and provide a systematic scheme for the choice of R-BHA.

2. Estimation of the reamer side force based on three moment equations

The formation of a borehole is the result of interaction between the reamer and the formation rock, and the trajectory of the borehole is affected by the reamer side force. The main factors affecting the reamer side force are the R-BHA used, the construction parameter and the borehole size. Therefore, it is necessary to study the reamer side force to scientifically control the bore trajectory. A set of equations has been derived to determine the bit side force based on three moment equations (Bai, 1982). On this basis, the reamer side force can be determined by further deriving some equations.

2.1. Assumptions

The mechanical model of the R-BHA was developed based upon the following assumptions:

(a) The R-BHA, composed of a reamer, drill pipe and centralizer, was a small elastic deformation system.
(b) The reamer axis coincided with the axis of borehole, and the contact between the reamer and bottom hole was regarded as a hinge.
(c) The pullback force and resistance were constant along the axis of the borehole.
(d) The contact between the R-BHA and the borehole wall was a point contact.
(e) The vibration of the drill string and mud were negligible and could be ignored.

2.2. Mathematical model of a two-centralizer R-BHA

A static mechanical model of a two-centralizer R-BHA in a borehole is shown in Fig. 2. The pullback force F and resistance f act on the axial direction of the drill stem center. Affected by the weight of the drill string, the drill pipe will be tangent to the borehole, and the cutting points of the front and rear drill pipes are T_1 and T_2, respectively. The R-BHA between the cut points is divided into four sections by the front centralizer, reamer and rear centralizer, and the lengths of the sections are L_1, L_2, L_3 and L_4, with unit weights of q_1, q_2, q_3, q_4, respectively. In the centralizer A, reamer B and centralizer C, the internal bending moments are M_1, M_2 and M_3, respectively.

At the reamer B, the reamer side force F_B is the lateral reaction force of the borehole to the reamer. When the direction of the actual reamer