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Study on open-hole extended-reach limit model analysis for horizontal drilling in shales

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ABSTRACT

The published extended-reach well (ERW) limit theory can be used to predict how far the horizontal ERW can extend. However, the use of this theory in shale formation remains poorly understood. Therefore, an open-hole extended-reach limit model of horizontal drilling in shales must be established based on the published ERW limit theory and models. First, the published models are modified for convenient practical calculation, and the core of this modified model is to predict the horizontal-section limit of horizontal ERW. The horizontal-section limit and the final open-hole extended-reach limit primarily depend on the annular pressure drop and fracture pressure in shales. Secondly, the characteristic of shale hydration swelling is considered. The stress state of the wellbore wall changes when the hydration stress is treated as a part of the effective stress. Moreover, the hydration stress can also significantly affect the horizontal-section limit and final open-hole extended-reach limit. In addition, a case study is performed, and the results indicate that the horizontal-section limit is 7292 m when there is no hydration stress, whereas it decreases by several thousand meters if the hydration swelling effect is considered. Finally, through the sensitivity analysis of the main factors in the modified model, the following results are obtained: the longer horizontal-section limit can be achieved in conditions with smaller flow behavior index, lower mud density, smaller mud flow rate, and lower temperature; meanwhile, a reasonable eccentricity range is also necessary, which is approximately 30–35 mm in this paper. The model in this paper provides a theoretical guidance for the optimization design method and operating parameters of horizontal ERW in shales to achieve a longer horizontal-section limit, which is significant for the use of shale gas.

1. Introduction

Extended-reach drilling (ERD), particularly horizontal ERD, has become an important method to develop oil and gas resources with low permeability and difficulty to use, such as shale gas (Michael, 2012). The open-hole extended-reach limit is the maximum measured depth (MD) of an extended-reach well (ERW), and the horizontal-section limit is the maximum MD of the horizontal section of a horizontal ERW, both of which can be used to assess the extension ability of a horizontal ERW. Moreover, several worldwide ERD true-vertical-depth (TVD) vs. horizontal-displacement (HD) charts are provided by Neil R and Andrew M, 2011 and Michael (2012), which show the limit cases of ERW that have been drilled within the existing technology and equipment capacity, and many remarkable records have been achieved. The horizontal well and hydraulic fracturing have become two important technologies in the development of shale gas; the longer horizontal section is expected to achieve higher oil and gas output. Consequently, drilling engineers are concerned about how far the horizontal section of horizontal ERW can extend and how to effectively break this limit. The theory of the open extended-reach limit can be used to address these questions.

Mason (1998) noted that the limits of ERD can be divided into the mechanical limit and the formation-related limit, and the formation-related limit is mainly related to the borehole stability or fracture gradient. However, there are no relevant models and calculating formulas. Luiz Alberto et al. (2003) mainly analyzed the effect of the water depth on the offshore ERD. He considered the problem of the ERD operation of ERD to be that the fracture

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pressure could not continue increasing in step with the increase in annular pressure drop when the MD of ERW increases. However, his article also lacks relevant calculating formulas.

Deli et al. (2009) considered that drilling operations are mainly confronted with three types of limits: open hole, hydraulic, and mechanical extended-reach limit. More specifically, the open-hole extended-reach limit, which is discussed in this paper, is related to the annular pressure drop and fracture pressure of a drilled formation. The concept of the open-hole extended-reach limit and its theory were also first proposed by Deli et al. (2009). Its basic principle is that the ERW certainly cannot extend without limitation during the drilling operation, and its extension is stopped when the bottom hole is fractured (Chengjin et al., 2006; Deli et al., 2009). Based on this theory, the basic model of the open-hole extended-reach limit is established, and the maximum depth D_m can be expressed as Eq. (1) at D_v, namely TVD. The advantage of this formula is its simplicity and clarity. Specifically, $\rho_f - \rho_m$ is the safe operation window of the drilled formation (g/cm^3), which belongs to the objective factor, and ρ_{dp} is the equivalent density of mud pressure loss in the unit-length annulus (g/cm^3), which represents the subjective factor, which can be artificially controlled.

$$D_m = \frac{\rho_f - \rho_m}{\rho_{dp}} D_v \tag{1}$$

Then, Sun Tengfei (2013) also performed the relevant research work in this field, and the following factors were simultaneously considered in his model, including the annular cutting concentration, cutting bed height, calculation error of equivalent circulating density (ECD), effect of the joint and collar, etc. Its essence is to refine the calculation process of the annular pressure drop, and the maximum depth D_m is more accurately calculate in Eq. (2).

$$D_m = \frac{\rho_f - \rho_m - C_a(\rho_s - \rho_m) - \Delta E}{\rho_{dp}} D_v \tag{2}$$

However, these two models have two main shortcomings. First, the parameter ρ_{dp} (equivalent density of mud pressure loss in the unit-length annulus) is introduced and considered a constant. In other words, the annular pressure drops of the unit-length in all sections, which include the vertical section, deviated section and horizontal section, are considered equal. However, it is unreasonable and difficult to determine its exact value unless D_m is known in advance. Second, these published models as universal models are relatively simple, which do not make a detailed analysis for a certain formation such as that in shales. Consequently, these models are more suitable for understanding the concept of the open-hole extended-reach limit instead of practical calculations. Therefore, to overcome those shortcomings, a modified model that is more suitable for practical calculations and involves the effects of shale hydration swelling must be developed.

The main objective of this paper is to establish an open-hole extended-reach limit model of horizontal drilling in shales. More specifically, the modified model is based on the previously published models; its greatest feature is the introduction of the pressure loss gradients of the horizontal section and the hydration stress in shales, and the core of this model is to predict the horizontal-section limit value. In the end, the sensitivity analysis is performed for those main parameters of the modified model, and the corresponding conclusions are also provided in this paper. In addition, the MATLAB environment is used to simulate the results because of the enormous computation burden and to ensure higher accuracy and efficiency of the calculation.

2. Modified model

First, the authors make the following assumptions:

(1). The ERW in this paper is the three-section horizontal ERW;
(2). The well is in an ideal borehole cleaning state; the effect of cuttings on the annular pressure drop is not considered, i.e., there is only single-phase flow in the annulus;
(3). The power law fluid is used to simulate the results in this paper;
(4). The eccentricity of the drill string is only considered in the large-inclination section and horizontal section. Moreover, there is only a uniformly eccentric annulus in these sections;
(5). The effects of the wellbore tortuosity and pipe string wall roughness on the annular pressure drop are ignored;
(6). The formation pressure system at the identical depth is identical, and the abnormal pressure system is ignored;
(7). The complex situation such as original formation cracks or potential cracks, bedding change, leakage of formation, etc. must be neglected;
(8). Because the oil-based mud is often used in shale formation, only the oil-based mud is discussed in this paper.

Based on the basic principle of the open-hole extended-reach limit, the horizontal ERW certainly cannot extend without limitation during the drilling operation and will stop extending at a critical point, which implies that the bottom hole pressure is equal to the fracture pressure of drilled formation. Thus, an open-hole extended-reach limit model of horizontal drilling in shales is established. First, we assume a simple three-section horizontal ERW, which includes a vertical section, a deviated section and a horizontal section. The basic principle is that the extension of horizontal ERW stops when the bottom hole formation is fractured during drilling at the critical point. Therefore, Eqs. (3) and (4) are obtained at the critical point in the normal drilling process.

$$\rho_m g D_v + \Delta p_a = \rho_f g D_v \tag{3}$$

$$\rho_m g D_v + (\Delta p_v + \Delta p_d + \Delta p_h) = \rho_f g D_v \tag{4}$$

Particularly, both MDs of the vertical section and deviated section are measured using an inclinometer before the drill bit enters the horizontal section; in other words, the lengths L_v and L_d of the vertical and deviated sections, respectively, are known. Therefore, the final open-hole extended-reach limit L_t is obtained only if the horizontal-section limit L_h is calculated.

The next step is to calculate the annular pressure drop Δp_h of the horizontal section at the critical point, which is expressed in Eq. (5).

$$\Delta p_h = \left(\rho_f - \rho_m\right) g D_v - (\Delta p_v + \Delta p_d) \tag{5}$$

The horizontal-section limit L_h can be achieved if the pressure loss gradient in the horizontal section $(\Delta p/\Delta L)_h$ is also calculated, and L_h is expressed in Eq. (6).

$$L_h = \frac{\Delta p_h}{(\Delta p/\Delta L)_h} \tag{6}$$

This analysis process is shown in Fig. 1. The core of this model is to predict the horizontal-section limit L_h. The mud hydrostatic pressure of the bottom hole line in Fig. 1 remains constant in the horizontal section. However, the mud dynamic pressure of the bottom hole line increases with drilling in the horizontal section because there is an annular pressure drop in all sections. Finally, the horizontal drilling stops extending at the critical point.