The challenge of ocean shallow extended reach wells: how to achieve a farther extension limit

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ABSTRACT: Due to the shallow vertical depth, offshore shallow extended reach wells usually have a high horizontal displacement to vertical depth ratio. The high friction of drill pipe during drilling limits the extension capacity of the extended reach well. Based on the three-dimensional string mechanical model, this paper analyzes the extension limit under the drilling condition and maximum running depth of 9-5/8 ″ casing under casing running conditions, and concludes that the friction coefficient, wellbore trajectory and drilling equipment are the main parameters limiting the extension limit. The operation parameters and suggestions under different working conditions are given.This research is expected to increase the extension limit of shallow extended reach wells and promote the economic and efficient development of shallow oil and gas.

Keywords: extended reach well, extension limit, shallow water, downhole string.

1 INTRODUCTION

Extended reach well technology is an essential means of unconventional oil and gas exploration and development (Chen et al., 2020; Payne & Abbassian, 1996). The extension limit of an extended-reach well is the maximum drillable depth of the drill string, which is affected by many aspects such as wellbore profile, wellbore cleaning, drilling fluid performance, bottom hole assembly, and rock drillability (Gao et al., 2009; Mason et al., 2003; Mirhaj et al., 2010). The frictional torque of the drill string is the main limiting factor for the horizontal extension capability. Shallow extended reach well is characterized by long horizontal section and not deep vertical depth. The inclined section of shallow extended reach well is shallow and has a long stable section, which increases the difficulty of drill pipe drilling and limits the extension limit during drilling.(Chen & Gao, 2017; Huang et al., 2016).

In this paper, the whole downhole pipe string is taken as the research object, and the pipe string mechanical model of extended reach well is established. Analyzes the extension limit under different conditions. This research is expected to increase the extension limit of shallow extended reach wells and promote the economic and efficient development of shallow oil and gas.

2 THEORETICAL MODELS

2.1 Pipe string mechanics model

The model assumptions are as follows:

(1) The cross section of the wellbore and the pipe string is a regular circle, and the contact type is sliding friction;

(2) Neglecting the influence of borehole clearance, the pipe string is in continuous contact with the borehole and the axis of the pipe string coincides with the borehole axis;

(3) The deformation of the pipe string is within the linear elastic range, ignoring the dynamic effect(Chen & Gao, 2017; W. Huang & Gao, 2019; Huang & Gao, 2022);

According to the basic equations of pipe string mechanics, the three-dimensional pipe string overall force model is deduced, and the axial force formula is:

$$\frac{d(-F)}{ds} = -EI\kappa_b \frac{d\kappa_b}{ds} - q\cos\alpha \mp \mu_1 \cdot n_t \tag{1}$$

Where "+" in "$\mp$" represents the pipe string running process, "-" represents the pipe string pulling process; F is the axial compressive force on the pipe string, N; s is the well depth, m; q is the gravity of the pipe string per unit length, N/m; α is the inclination angle, rad; EI is the bending stiffness of the pipe string, $\mathrm{N/m^2}$; n_t is the contact distribution force between the pipe string and the borehole, N/m; μ_1 is the axial friction coefficient of the pipe string; κ_b is the borehole axis curvature, $\mathrm{m^{-1}}$. Its calculation formula is as follows:

$$\kappa_\mathrm{b} = \sqrt{\left(\frac{d\alpha}{ds}\right)^2 + \sin^2\alpha\left(\frac{d\phi}{ds}\right)^2} \tag{2}$$

Where ϕ is borehole axial azimuth, rad.

$$\frac{dM_T}{ds} = -\frac{1}{2}\mu_2 \cdot n_t \cdot D_b \tag{3}$$

Where M_T is the torque on the pipe string, $\mathrm{N \cdot m}$; μ_2 is the circumferential friction coefficient of the pipe string rotation; D_b is the outer diameter of the pipe string, m.

$$M_b = EI\kappa_b \tag{4}$$

Where M_b is the bending moment on the string, $\mathrm{N \cdot m}$.

The formula for the distribution of contact force on the pipe string is:

$$n_t = \sqrt{\frac{A^2 + B^2}{1 + \mu_2^2}} \tag{5}$$

The calculation formulas of A and B are:

$$A = EI\frac{d^2\kappa_b}{ds^2} + \kappa_b F - \kappa_n(-\kappa_b M_T + EI \cdot \kappa_b\kappa_n) + \frac{q}{\kappa_b}\frac{d\alpha}{ds}\sin\alpha \tag{6}$$

$$B = \frac{d}{ds}(-\kappa_b M_T + EI \cdot \kappa_b\kappa_n) + EI \cdot \kappa_n\frac{d\kappa_b}{ds} - \frac{q}{\kappa_b}\frac{d\phi}{ds}\sin^2\alpha \tag{7}$$

Where κ_n is the torsion of the borehole axis, and its calculation formula is as follows:

2.2 Extension limit calculation model

Within the constraints of drilling technology and drilling equipment, the drilling depth of an extended-reach well has a limit value, which is the extension limit of the extended-reach well. The calculation in this paper only considers the mechanical extension limit, without considering hydraulic factors, and only optimizes the extension limit from the perspective of pipe string mechanics.

2.2.1 Drilling conditions

The drilling process is divided into sliding drilling and rotary drilling. The main factors that constrain the mechanical extension limit of the horizontal section of extended reach wells are the drilling rig performance, bit drilling capacity, and drill string failure. For sliding drilling, only the surface hook rated load, drill string yield failure, and bit rock-breakout threshold drilling pressure are considered as constraints.

$$L_{\max} = \{T_l, \sigma, F_b\} \tag{8}$$

Where $L_{\max}$ is the extension limit, m; T_l is the axial force on the pipe string, N; σ is the axial compressive force on the pipe string, N; F_b is the weight on the drill bit, N;

In rotary drilling, in addition to the conditions to be considered in sliding drilling, there are also the turntable rated torque and the rock-breaking threshold torque of the drill bit as constraints.

$$L_{\max} = \{T_l, \sigma, T_b, M_l, M_b\} \tag{9}$$

Where M_l is the torque on the pipe string, $\mathrm{N \cdot m}$; M_b is the torque on the drill bit, $\mathrm{N \cdot m}$.

2.2.2 Casing running conditions

The casing running operation has three operating modes: sliding casing running, rotating casing running and floating casing running.

When sliding the casing operation, the surface hook rated load and the yield failure of the pipe string are considered as constraints.

$$L_{\max} = \{T_l, \sigma\} \tag{10}$$

When rotating the casing operation, the surface hook rated load, the yield failure of the pipe string, and the rated torque of the turntable are considered as constraints.

$$L_{\max} = \{T_l, \sigma, M_l\} \tag{11}$$

The effective axial and lateral friction forces are a function of the actual friction force when rotating. If the running speed is fast and the rotation speed is slow, most of the friction is in the axial direction. If the running speed is slow and the rotation speed is fast, most of the friction is in the circumferential direction. The key is to convert axial friction into circumferential friction.

$$\mu_a = \frac{V_m}{\sqrt{V_m^{\ 2} + V_t^2}} \mu \tag{12}$$

$$\mu_t = \frac{V_t}{\sqrt{V_m^{\ 2} + V_t^2}} \mu \tag{13}$$

$$V_t = \frac{2\pi n}{60} \frac{D_t}{2} \tag{14}$$

Where , μ_a is the axial friction coefficient; μ_t is the circumferential friction coefficient; μ is the sliding friction coefficient; n is the rotational speed, $\mathrm{min^{-1}}$; D_t is the outer diameter of the pipe string, m; V_m is the axial movement speed, m/s; V_t is the circumferential movement speed, m/s.

The corresponding well depth is found through the value of the critical resistance angle, and this well depth is the initial placement position of the floating coupling. Draw the relationship curve between the wellhead hook load and the corresponding floating length, and the floating length corresponding to the maximum wellhead hook load point is the best.

$$\theta_c = \tan^{-1}\left(\frac{1}{\mu}\right) \tag{15}$$

Where, θ_c is the critical drag angle, °; μ is the coefficient of friction between the casing and the borehole.

3 EXAMPLE ANALYSIS

The stability angle of the extended reach well on platform A is relatively large in the range of 70 °~85 °, and the length of the deflecting section is in the range of 100 m~250 m. Take A1H well as an example to carry out the calculation and analysis of the extension limit, and its well trajectory is build-hold-build. The second spud hole size of A1H well is 12-1/4″, the casing size is 9-5/8″, the casing running analysis shows that the hole size is 311.2mm, and the casing outer diameter is 244.5mm.

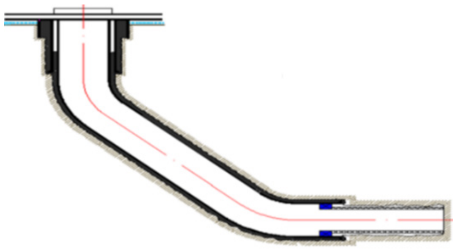

Figure 1. Well bore structure diagram of Well A1H.

Table 1. Well trajectory parameters of A1H well.

Depth	[m]	3703
True vertical depth	[m]	1092
Horizontal displacement	[m]	2795
Kick off point	[m]	145
Hold angle	[°]	82
Build-up rate	[°/m]	2.45
Length of stabilizing section	[m]	1651
Horizontal displacement to vertical depth ratio	[-]	2.5

3.1 Mechanical analysis of pipe string

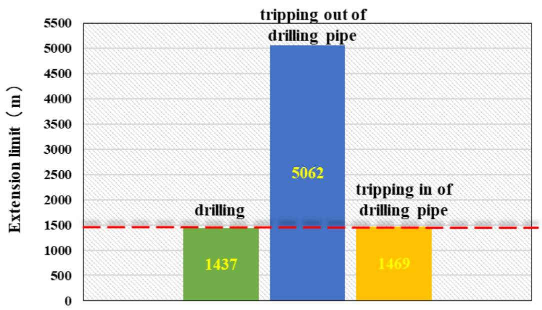

Figure 2. Horizontal section extension limit of A1H well under different conditions.

The above three conditions are mainly restricted by drilling conditions. The kick off point is shallow and the build-up rate is large, so the hold angle is large. With the increasing of the vertical depth of the kick off point, the extension limit increases obviously; The extension limit of horizontal section is inversely proportional to the friction coefficient. The main factors limiting the extension limit of sliding drilling are well structure and friction coefficient. The extension limit of the horizontal section can be increased by reducing the friction coefficient and increasing the deflection point. The rated torque and friction coefficient of the drill disc are the main factors limiting the rotation. According to the drilling situation, the inverted drilling tool and tower drilling tool assembly are adopted to reduce the buckling risk of the pipe string. At present, the lifting capacity of the modular drilling rig is 315t, and the torque is 55KN·m. Improving the performance of the drilling rig can significantly improve the extensibility of the extended reach well. Rotary drilling or composite drilling shall be adopted.

Well A1H is the deepest well in the 12-1/4 ″ section of platform A. According to the calculation results under casing running conditions, when the friction coefficient of the open hole section is greater than 0.40, buckling will occur during casing running. When the friction coefficient is 0.30 in the casing and 0.45 in the open hole section, the 47PPF, 9-5/8 ″ casing is lowered to 3300m at the deepest, which does not meet the operation requirements.

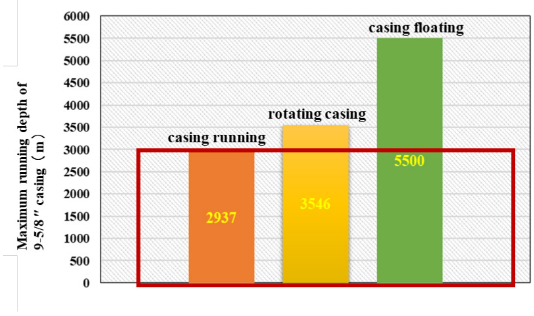

Figure 3. Maximum running depth of 9-5/8 ″ casing under different conditions-

The hold angle of inclination and the friction coefficient of the open hole section are the two main factors that restrict the casing working conditions. The extension limit decreases with the increase of well deviation; With the decrease of friction coefficient, the extension limit increases. In addition to the influence factors of conventional casing running, casing running speed and rotating speed are the two key factors affecting the running of rotating casing. The limit running depth of casing is proportional to the casing speed and inversely proportional to the running speed. When rotating the casing, the recommended casing rotation speed is 20r/min and the casing running speed is 0.5m/s.

It can be seen from the three casing running conditions that floating casing running mode is recommended. In order to meet the requirements of well control and the initial depth of oilfield logging, the depth of surface casing can be increased as much as possible. So as to ensure the subsequent casing running. Reasonably use drag reduction tools, such as installing rotary joints and drag reduction joints.

3.2 Drilling equipment analysis

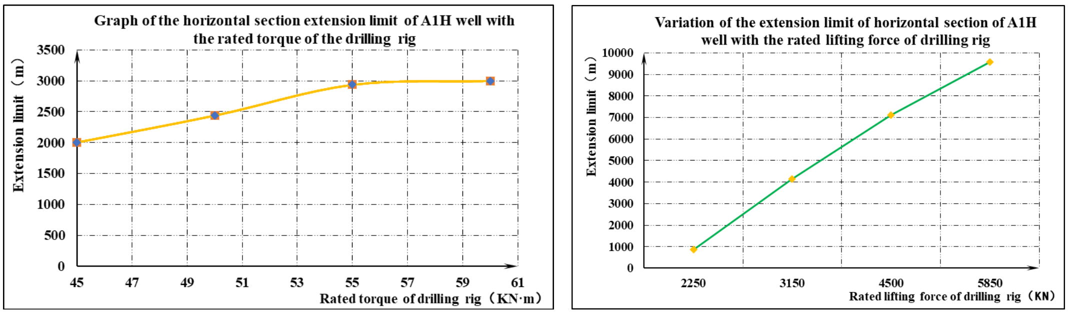

Figure 4. Variation of horizontal section extension limit with drilling rig parameters.

During rotary drilling, the main factor limiting the extension limit is the rated torque of the drill; The limiting factor under tripping condition is the maximum rated lifting force of the drill; Improving the performance of drilling rig can improve the hole extension limit.

4 CONCLUSION

1. The main factors limiting the extension limit of sliding drilling are well structure and friction coefficient. The extension limit of the horizontal section can be increased by reducing the friction coefficient and increasing the deflection point. According to the drilling situation, the inverted drilling tool and tower drilling tool assembly are adopted to reduce the buckling risk of the pipe string. Rotary drilling or combined drilling is recommended.

2. The hold angle of inclination and the friction coefficient of the open hole section are the two main factors that restrict the casing working conditions. It is recommended to optimize the wellbore structure, such as stable slope angle. It is recommended to run casing by rotating or floating. When rotating the casing, the recommended casing rotation speed is 20r/min and the casing running speed is 0.5m/s.

3. At present, the lifting capacity of the modular drilling rig is 315t, and the torque is 55KN · m. Improving the performance of the drilling rig can significantly improve the extensibility of the extended reach well.

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