DOI 10.1007/s12182-009-0026-8

Limit analysis of extended reach drilling in South China Sea

Gao Deli[1]*, Tan Chengjin[1] and Tang Haixiong[2]

[1] MOE Key Laboratory of Petroleum Engineering, China University of Petroleum, Beijing 102249, China
[2] CNOOC China Limited-Shenzhen, Shenzhen, Guangdong 518067, China

Abstract: Extended reach wells (ERWs), especially horizontal extended reach well with a high HD (horizontal displacement) to TVD (true vertical depth) ratio, represent a frontier technology and challenge the drilling limitations. Oil and gas reservoir in beaches or lakes and offshore can be effectively exploited by using extended reach drilling (ERD) technology. This paper focuses on the difficult technological problems encountered during exploiting the Liuhua 11-1 oil field in the South China Sea, China. Emphasis is on investigating the key subjects including prediction and control of open hole limit extension in offshore ERD, prediction of casing wear and its prevention and torque reduction, ϕ244.5mm casing running with floating collars to control drag force, and steerable drilling modes. The basic concept of limit extension in ERD is presented and the prediction method for open hole limit extension is given in this paper. A set of advanced drilling mechanics and control technology has been established and its practical results are verified by field cases. All those efforts may be significant for further investigating and practicing ERD limit theory and control technology in the future.

Key word: Extended reach drilling, deep-water drilling, limit analysis, downhole tubular mechanics, drag and torque, wellbore instability

1 Introduction

When the horizontal displacement (HD) of a directional or horizontal well is more than 3,000 m and the HD to true vertical depth (TVD) ratio $\lambda \geq 2.0$ or the measured depth (MD) to TVD ratio $k \geq 2.0$, the directional or horizontal well is called a extended reach well (ERW). When λ or k is more than 3.0, the well is called a high HD to TVD ratio or high MD to TVD ratio ERW (Blikra et al, 1994). Extended-reach drilling (ERD) is a frontier technology in drilling limitations (Payne et al, 1994; CPS, 2008). In offshore drilling, extended-reach wells can be drilled from one platform to develop the surrounding satellite oil & gas reservoirs. Moreover, ERD technology can also be used to develop some marginal oil and gas reservoirs that can not be exploited easily. ERD technology can be used to exploit offshore or lake oil and gas resources from onshore or land sites with lower economic and environmental costs.

The Liuhua 11-1 oil field in the South China Sea, China was put into production in 1996. It is a self-contained offshore oilfield with the largest geological reserve at that time in China with deep water of 311 meters (Wei and Tang, 2005; Wei et al, 2006). The average water cut of existing production wells in this oilfield was more than 98% at the end of 1998. No. 3 reservoir, located at more than 4.5 km from the major producing area, had to be developed to stabilize oil production. It is recommended to use ERW with a high HD to TVD ratio to exploit this reservoir using the existing floating drilling and production systems and wellheads in the major producing area to sidetrack ERWs to the No. 3 reservoir. This operation presented several major challenges including: (1) Because the deep-water oil reservoir is at a shallow depth (only 900 m under mud line), the formation has a low pressure-bearing capacity and a long holding open hole section with a high hole angle (80°-85°) is liable to lost circulation and fracture so the extension of the open hole section is difficult during ERD; (2) In the buildup sections and the highly deviated sections having inclinations of 80-85 degrees, torque and drag caused by rotating drill string (Michell et al, 2007) are very high with serious casing wear, and the drag force is also very large in casing running, so the whole operation is high risk; (3) The high buildup rate in a large wellbore makes kick off and sidetracking operations difficult, and the trajectory in long holding sections is prone to drift so rotary steerable drilling is difficult.

As a result, innovative research was done on some key technologies, including prediction and control of the limit extension of ERD open hole, prediction of casing wear, wear prevention and torque reduction (Schamp and Estes, 2006), reducing the drag force in ϕ244.5mm casing running operation, and steerable drilling modes. This research resolved some difficulties in extended reach drilling engineering and ensured the smooth progress of the high HD to TVD ratio ERD project for exploitation of the Liuhua 11-1 oilfield.

*Corresponding author. email: gaodeli@cup.edu.cn
Received December 18, 2008

2 Basic concepts of ERD limit extension and prediction methods

There is a limit of measured depth for each ERD operation under some restrictions by subjective and objective conditions. The limit value is named the limit extension of ERD. Three types of limit status, i.e., the open hole limit extension, the mechanical limit extension, and the hydraulic limit extension, should be considered during ERD design and operations. The open hole limit extension is the measured depth of an ERW when the bottom hole is fractured during ERD operation, and is mainly dependent on the formation fracture pressure of the formation being drilled and the annular pressure loss of drilling fluids. The mechanical limit extension includes the drillstring operation limit and the casing running limit, and is mainly dependent on the steerable drilling modes (slide or rotary steerable modes), tubing strength, drilling string and casing loads, and rig drive capacity. The hydraulic limit extension is the maximum measured depth in ERD operation under the conditions that hydraulic parameters can keep normal circulation and hold a good hole cleaning, which is mainly dependent on the hydraulic equipment, drillstring and surface manifold conditions, hydraulic parameters, and penetration rate. In optimum design and risk analysis for ERD projects, the open hole limit extension, mechanical and hydraulic capability should be quantitatively evaluated according to the practical formation characteristics and equipment used, and the smallest limit value among the aforesaid three limit extensions is taken as the limit allowance for ERD operations.

Assuming that $D_{\rm M}$ is the measured depth, $D_{\rm V}$ is the true vertical depth, and $D_{\rm H}$ is the horizontal displacement of a ERW, so the ratio of MD to TVD, k, and the ratio of HD to TVD, λ can be expressed as follows:

$$k = \frac{D_{\rm M}}{D_{\rm V}} \tag{1}$$

$$\lambda = \frac{D_{\rm H}}{D_{\rm V}} \tag{2}$$

The combination of Eqs.(1) and (2) gives

$$\lambda = k\frac{D_{\rm H}}{D_{\rm M}} \tag{3}$$

According to Eqs. (1) and (2) , the limit extension in ERD operation can be represented by the allowable limit value of k (or λ), i.e. $k_{\rm L}$ (or $\lambda_{\rm L}$). The basic concepts of measured depth and horizontal displacement indicate that $D_{\rm M}>D_{\rm H}$, so $\lambda<k$, which means that HD to TVD ratio λ is always less than the MD to TVD ratio k for the same ERW. Obviously, for an ERW being drilled in a particular pay zone, the HD to TVD ratio and the MD to TVD ratio increase with increasing measured depth and horizontal displacement, but the allowable limit value, $\lambda_{\rm L}$ does not equal or exceed the allowable limit value $k_{\rm L}$, that is $\lambda_{\rm L}<k_{\rm L}$.

Considering the pressure balance of down hole, we can define the measured depth, at which the formation is fractured by high bottom hole fluid pressure, as the open-hole limit extension, so the relationships between the formation fracture pressure gradient, drilling fluid density, and equivalent density of annular pressure loss can be established for predicting the MD to TVD ratio ($k_{\rm L0}$) of the open hole limit extension in ERD and the maximum casing running depth ($D_{\rm M}^{\rm L}$). For specific target zones, if the equivalent density of annular pressure loss is constant, $k_{\rm L0}$ and $D_{\rm M}^{\rm L}$ can be calculated by following expressions:

$$k_{\rm Lo} = \frac{\rho_{\rm f} - \rho_{\rm m}}{\rho_{\rm dp}} = \frac{\Delta\rho_{\rm fm}}{\rho_{\rm dp}} \tag{4}$$

$$D_{\rm M}^{\rm L} = k_{\rm L} D_{\rm V} = \frac{\Delta\rho_{\rm fm}}{\rho_{\rm dp}} D_{\rm V} \tag{5}$$

where $\rho_{\rm m}$ is the drilling fluid specific gravity, g/cm^3; g is the gravity acceleration and equal to 9.81 m/s^2; $D_{\rm V}$ is the true vertical depth at which the formation is fractured, m; $\rho_{\rm f}$ is the equivalent density of the formation fracture pressure, g/cm^3; $\rho_{\rm db}$ is the equivalent density of drilling fluid pressure loss in annulus, g/cm^3; $\Delta\rho_{\rm fm}$ is the safe drilling fluid density window of the formation to be drilled, g/cm^3.

For particular target zones or ERD programs, the true vertical depth, drilling fluid density, and the formation pressure characteristics have their specific values. If adopting overpressure-balanced drilling mode and specific technologies to control annular pressure loss, $\Delta\rho_{\rm fm}$ and $\rho_{\rm dp}$ will be predetermined so that the allowable value $k_{\rm L}$ of the open hole limit extension can be determined by Eq. (4). The calculation results can clearly show the effect of drilling fluid pressure loss in the annulus on $k_{\rm L}$ (as shown in Fig 1), in which $k_{\rm L}$ decreases significantly with the increase in the equivalent density ($\rho_{\rm dp}$) of drilling fluid pressure loss in the annulus and at the same time increases with the enlargement of the safe drilling fluid window ($\Delta\rho_{\rm fm}$) decided by the formation fracture pressure (equivalent density $\rho_{\rm f}$) and drilling fluid density. Drilling fluid pressure loss in the annulus is a key controllable factor influencing the ERD limit extension. Supposing that the other factors do not change, the ERD open hole limit extension and casing running depth can only be increased by reducing the annular pressure loss. For the same reason, reducing the annular pressure loss is also a main way to simplify the hole structure. Thus, when drilling the laterally (or horizontally) extended section of an ERW with a high HD to TVD ratio, taking comprehensive technological measures (such as reaming the open hole while drilling) to reduce the annular pressure loss can effectively increase the allowable limit extension of ERD without passively increasing the number of casing strings and reduce simultaneously potential risks such as lost circulation during drilling.

With the above discussion, $k_{\rm L}$ is decided by the formation pressure characteristics, drilling fluid density, and equivalent density of drilling fluid pressure loss in the annulus, but $\lambda_{\rm L}$ is not only related to these factors, but also has a close relationship with the practical wellbore trajectory. Thus, λ_L can indicate the technical difficulty of ERD more comprehensively and the concept of the HD to TVD ratio is used widely in practical ERD engineering. At the same time, the concept of the MD to TVD ratio is an important reference for optimum design and the risk evaluation and control in ERD engineering.

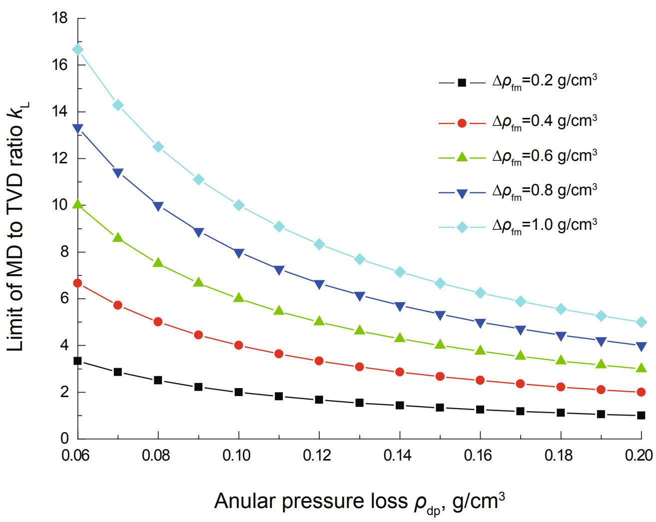

Fig. 1 Effects of ρ_{dp} and $\Delta\rho_{fm}$ on the ratio k_L

The formation evaluation result (Yu et al, 2006) shows that there is the formation in-situ stress state of the overburden stress $\sigma_V > \sigma_H > \sigma_h$ (σ_V is the overburden stress, σ_H is maximum horizontal stress, σ_h is minimum horizontal stress) in the Liuhua11-1 oil field. The azimuth of the maximum horizontal stress is 140°-150°. It is prone to lost circulation when drilling an ERW with a high HD to TVD ratio due to the lower magnitude of the in-situ stress in horizontal direction. Let the drilling fluid density equal to the equivalent density of the formation collapse pressure and the true vertical depth of horizontal section in an ERW be 1,208 m in the Liuhua 11-1 oil field so that the prediction chart (see Fig. 2) of the open hole limit extension for ERD into the argillutite formation in the oil field can be illustrated by Eq. (5) on the basis of evaluation results for fracture pressure and collapse pressure of the formations.

The early quantitative warning of rock cuttings bed in ERD made by real-time monitoring of equivalent circulating density (ECD) at bottom hole and multi-phase fluid simulation in the annulus, is helpful in the safe control of actual drilling operations. A clean and smooth hole can be kept by achieving managed pressure drilling with continuous circulation system and reducing down hole pressure by reaming while drilling. The rock strength of the open hole can be increased by shielding and temporarily blogging the formation, so that it is safer to extend the open hole drilling limit of an ERW with a high HD to TVD ratio.

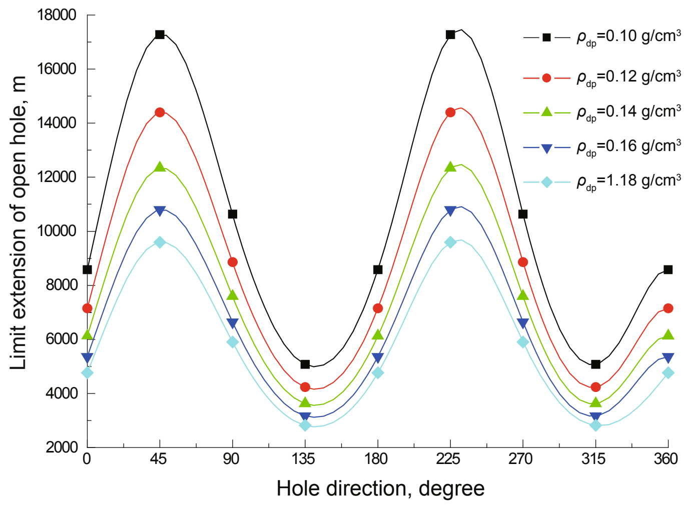

Fig. 2 Effects of hole direction on the open hole limit extension (1208m TVD)

3 Steerable drilling modes for ERD engineering

using mechanical theory for the steerable control of wellbore trajectory, a program for directional control calculations in steerable drilling was developed by the authors (Gao and Tan, 2006) and thus steerable drilling modes were established to control wellbore trajectory in an ERW with a high HD to TVD ratio by a series of bottom hole assemblies developed jointly with the bit manufacturer. Particularly, the trajectory drift of the long holding section in the ERW can be effectively controlled in rotary steerable drilling mode with a matched bit. As a result, the highly-inclined holding drilling of 4,380 m in Well B3ERW4 was successfuly finished by rotary steerable drilling with one PDC bit in the Liuhua11-1 oil field.

Based on actual field practice, two modes of steerable drilling for ERD engineering were presented, i.e. sliding steerable drilling with a steerable motor for the short HD section of ERW and rotary steerable drilling with a special rotary steerable tool for the long highly-inclined holding section of ERW. The two modes were successfully used to control the wellbore trajectory of ERW with a high HD to TVD ratio in the Liuhua11-1 oil field. The steerable motor in the sliding drilling mode was used in sidetracking the ϕ444.5mm kick off section. Rotary steerable drilling was adopted during drilling the long holding section of ϕ311mm diameter and the horizontal section of ϕ216mm diameter. In Well C1ERW5, the critical measured depth of mechanical limit extension for the sliding drilling mode was about 3,000 m by the drillstring drag simulations (Gao et al, 2002; Gao and Tan, 2003), taking the drillstring drag factor as 0.30 (Gao and Tan, 2006) shown in Fig. 3, and the rotary steerable drilling mode must be used after the critical measured depth.

4 Technique of casing wear prevention and torque reduction in ERD

Casing wear in ERW drilling depends on the casing and

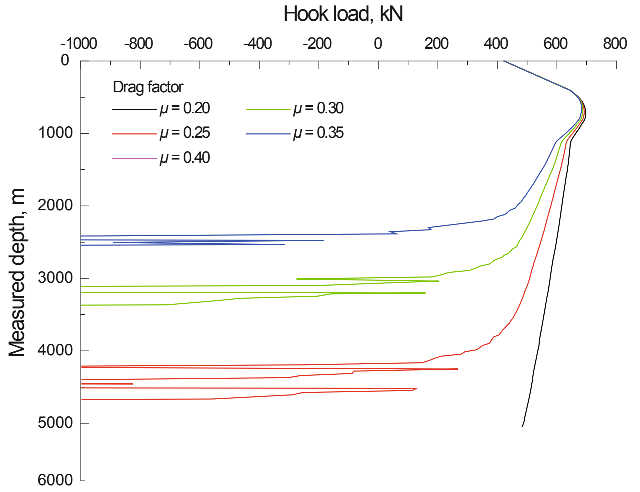

Fig. 3 Changes of drillstring hook load with measured depth while drilling into C1ERW5 well in the mode of sliding drilling

drill pipe material properties, media (drilling fluid) properties, friction factor, contact force between casing inner side and the surface of drill pipe joints, and accumulative distance of relative movement. Thus, the effective ways to decrease casing wear (Gao, 2006; Schamp and Estes, 2006) include increasing casing hardness, enhancing the lubricating property of drilling fluids (reducing friction drag factor), and reducing contact force and accumulative distance.

Casing wear severity can be quantitatively predicted according to ERW path design data to optimize the material grade and wall thickness of casing in the hole sections where the casing is liable to wear. A program to calculate placements of the downhole tools was developed by the authors (see Fig. 4). These can be used in the ϕ339.7 mm casing in the curved portion of REWs to alleviate casing wear and reduce the friction drag. A new design method for casing wear prevention and torque reduction in ERD was recommended for the project to replace the traditional drillstring design (Gao et al, 2006; Zhang et al, 2007).

ϕ339.7mm casing wear was predicted in Well C1ERW5 in the Liuhua 11-1 oil field. The maximum length of ϕ311.15mm hole section is 3,991 m (5,041-1,050 m). The average rate of penetration (ROP) is 10 m/h and the average rotary speed of drill string is 120 rpm. The friction factor is 0.25, calculated contact force 600 N/m, and wear factor is 5.221×10^{-3} GPa^{-1}. The outer diameter of the joint is 177.8 mm and the inner diameter of ϕ339.7mm casing is 313.605 mm (casing wall thickness 13.06 mm). Thus, the casing wear groove is 10.5 mm in depth which can be calculated according to the flow chart as shown in Fig. 4.

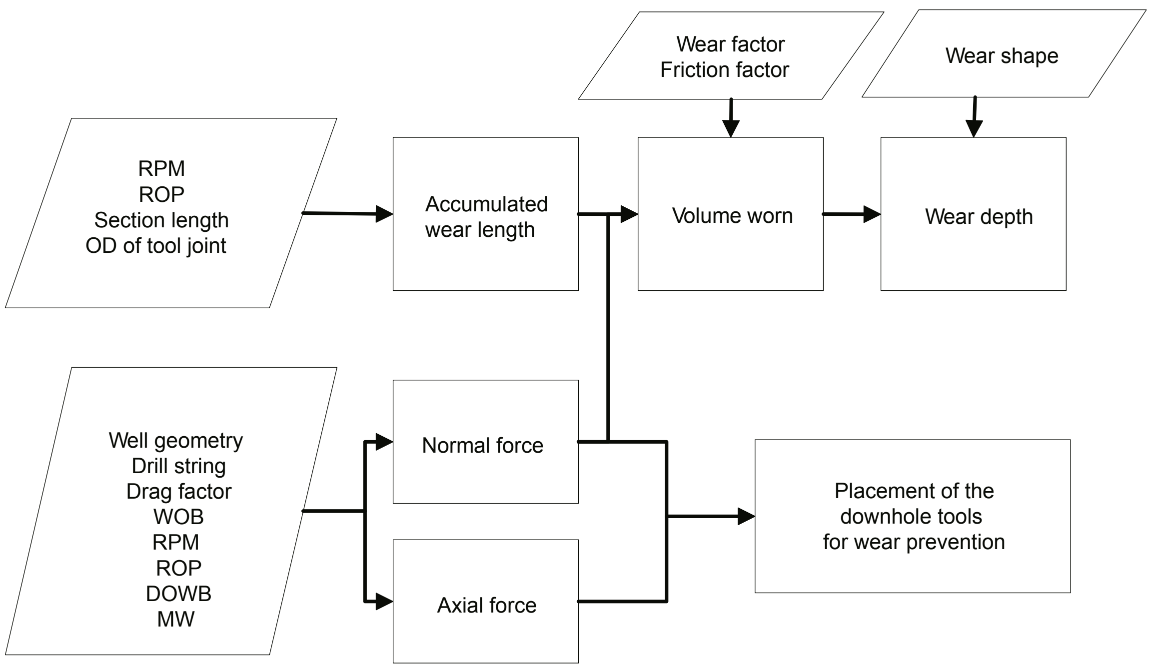

Fig. 4 Flow chart for casing wear prediction and prevention
Notes: RPM=Revolutions per minute, ROP=Rate of penetration, WOB=Weight on bit, DOWB=Diameter of well bore, MW= Drilling fluid density, Section length=Section length to be drilled

5 Drag reduction technique for casing running in ERW

A program for predicting the casing running drag in ERWs was developed using tubular mechanics (Gao, 2006), as shown in Fig. 5. This can be used to simulate different casing running methods, including conventional casing running, conventional air-filled casing running, totally air-filled casing running, and casing floatation running with floating collar. Except some commonly-used data, the drag factor between casing and borehole must be given beforehand. For the casing floatation running, the place of floating collar and the heavy mud density must be calculated in ERD engineering design.

The simulation results of different casing running ways include the relationship between hook load and measured depth of casing running and the axial force distribution of casing string along the well depth. A program was developed to calculate the best location of floating collars in casing floatation running and a series of techniques for ERW casing design and drag reduction were developed in the project to optimize the casing structure and the casing running mode for controlling effectively the drag force during casing running. The limit depth of ϕ244.5mm casing running into ERWs was been extended to more than 5,000 m measured depth.

To ensure smooth casing running into ERW, comprehensive measures should be taken to reduce the drag force during casing running operations. Except taking the casing floatation running mode, other measures, such as cutting guide float shoe, roller casing centralizer, and helical casing centralizer with low drag and torque, should be considered in the casing running design. In the Liuhua 11-1 oil field, if the running depth of ϕ244.5mm casing in the ERW is expected to reach to more than 5,000 m measured depth, it will be possible to increase the measured depth of ϕ339.7mm casing running from 1,050 m to 2,300 m so that the friction factor in the cased hole can be reduced from 0.55 in the open hole to 0.10 by using roller centralizers inside the ϕ339.7mm casing, as shown in Fig. 6.

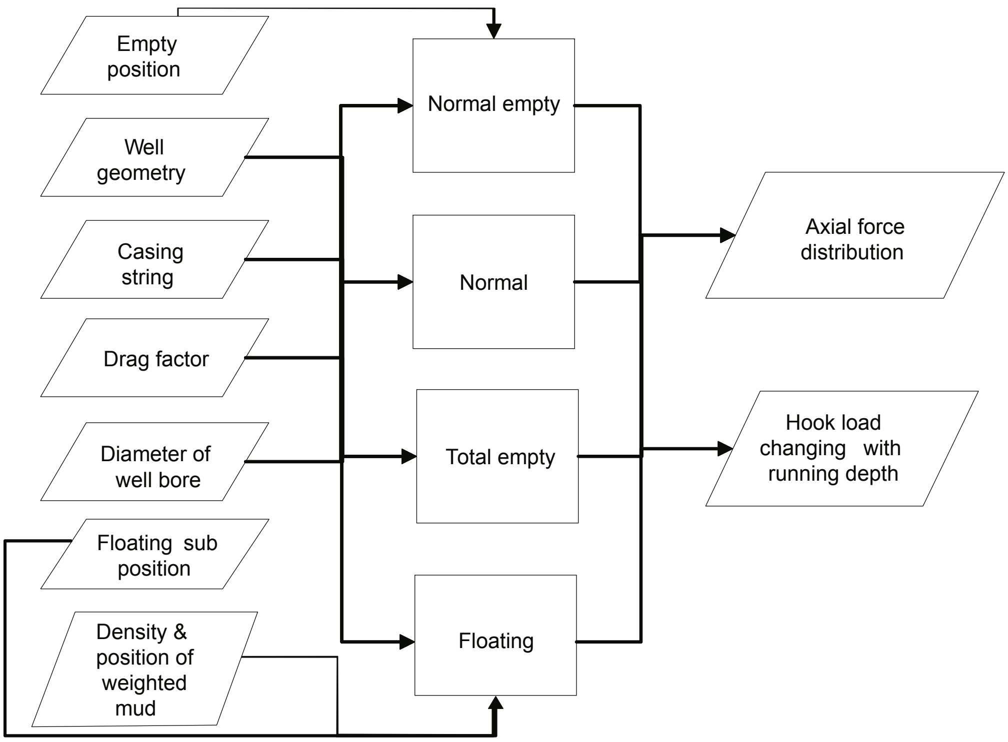

Fig. 5 Flow chart for ERW casing running simulation

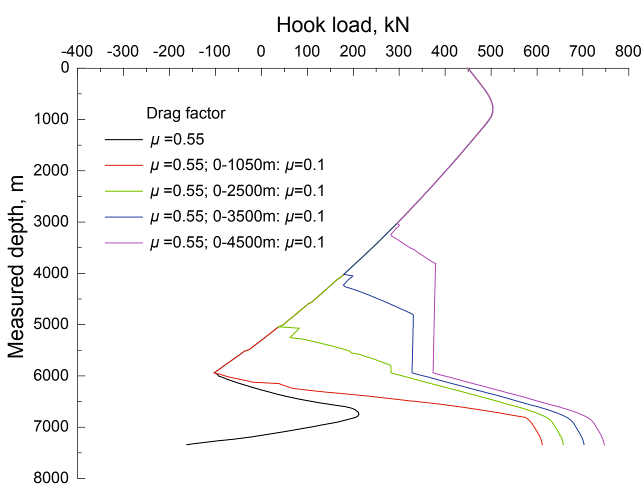

Fig. 6 Changes of hook loads with measured depth for prediction of ERW casing running in Liuhua 11-1 oil field

6 Conclusions

1) The open hole limit extension of MD to TVD ratio in ERD operation depends on the safe density window of the formation for drilling fluid weight and the actual control level of drilling annular pressure loss. It is an important criterion for us to evaluate drilling program design and risk control of the ERD engineering. Drilling in the direction of maximum horizontal in-situ stress in the formation poses more risk than drilling in other directions.

2) The special drillstring sub with the function of casing wear prevention and torque reduction inside casing should be used in ϕ311mm and ϕ216mm hole sections in ERW to prevent the intermediate casing from wearing and to reduce downhole torque load. It is predicted that the torque in ϕ216mm hole section in ERW can be reduced by 25%.

3) Increasing the ϕ339.7mm casing running depth is

beneficial to drag force reduction during the ϕ244.5mm casing running and the casing wear prevention and torque reduction during drilling operation of the ϕ311mm open hole for the ERD.

4) Considering comprehensively the technological and economic factors, sliding steerable drilling mode should be used for directional drilling into the short horizontal sections and rotary steerable drilling mode used for extended-reach drilling sections in ERW. Matching ability of rotary steerable tools with the drill bit type should be specially noticed in directional drilling design for the long holding section in ERW with a high HD to TVD ratio.

Acknowledgements

The financial support from the project of CNOOC China Limited-Shenzhen (Grant No. Z2007SLSZ-034) and the foundation project of the State Key Laboratory of Petroleum Resource and Prospecting (Grant No. PRPDX2008-08) is gratefully acknowledged.

References

Blikra H, Drevdal K E and Aarrestad T V. Extended reach, horizontal, and complex design wells: challenges, achievements and cost-benefits. The 14th World Petroleum Congress held in Stavanger, Norway, 29 May-1 June 1994. University of Tulsa Centennial Petroleum Engineering Symposium, 29-31 August 1994, Tulsa, Oklahoma (SPE 28005)

CPS (Chinese Petroleum Society). Report on Advances in Petroleum Engineering (2007-2008). Beijing: Chinese Science & Technology Press. 2008 (in Chinese)

Gao D L. Down-hole Tubular Mechanics and its Applications. Dongying, Shandong: China University of Petroleum Press. 2006. 65-120 (in Chinese)

Gao D L, Liu F W and Xu B Y. Buckling behavior of pipes in oil & gas wells. Progress in Natural Science. 2002. 12(2): 126-130 (in Chinese)

Gao D L and Tan C J. Research on numerical analysis of drag & torque for Xijiang extended-reach wells in South China Sea. Oil Drilling & Production Technology. 2003. 25(5): 7-12 (in Chinese)

Gao D L and Tan C J. Numerical analysis of downhole drag & torque and rotary steering system for Liuhua mega-extended reach wells in South China Sea. Oil Drilling & Production Technology. 2006. 28(1): 9-12 (in Chinese)

Gao D L, Zhang H, Pan Q F, et al. Study on rock mechanics parameters and drill bit selections for Liuhua oilfield in South China Sea. Oil Drilling & Production Technology. 2006. 28(2): 1-3, 6 (in Chinese)

Michell R F and Samuel R. How good is the torque-drag model? 2007 SPE/IADC Drilling Conference held in Amsterdam, Netherlands, 20-22 February 2007 (SPE/IADC 105068)

Payne M L, Cocking D A and Hatch A J. Critical technologies for success in extended reach drilling. SPE 69th Annual Technical Conference and Exhibition held in New Orleans, Louisiana, USA, 25-28 September 1994 (SPE 28293)

Schamp J H and Estes B L. Torque reduction techniques in ERD wells. IADC/SPE Conference held in Miami, Florida, USA, 21-23 February 2006 (IADC/SPE 98969)

Wei H A and Tang H X. Extended-reach drilling extends life of CNOOC field. Oil & Gas Journal. 2005. 103(29): 35-37

Wei H A, Mao Z, Xu Q and Yong C H. Extended-reach drilling techniques find application in Liuhua oil field. The 2006 SPE International Oil & Gas Conference and Exhibition held in Beijing, China, 5-7 Dec 2006 (SPE 103884)

Yu B H, Deng J G and Gao D L. Borehole stability analysis for mega-extended reach wells in Liuhua oil field at South China Sea. Oil drilling & production Technology. 2006. 28(1): 1-3 (in Chinese)

Zheng C K, Tan C J and Gao D L. Proper location of drag-reducer in ERD wells. Natural Gas Industry. 2007. 27(3): 66-68 (in Chinese)

(Edited by Sun Yanhua)