Limit of Horizontal Wellbore in Extended Reach Drilling with Gas

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DEDICATION

I would like to give my special appreciation to my parents and my wife with their endless love and support. Your love will encourage me to move forward. Love you all, my sincere father and mother! Share the life with you, my lovely wife!

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LIST OF ABBREVIATIONS

W_{cr}	The Critical Weight on Cutter (WOC), N
A_w	The Cutter Wear Flat Area, cm^2
α	Energy Partitioning Fraction, dimensionless
f	Thermal Response Function, dimensionless
K_f	Friction Coefficient between Cutter and Rock
v	Cutting Speed, m/s
T_{cr}	Critical Cutter Wear Flat Temperature, ^oC
T_{fl}	Fluid Temperature, ^oC
n	Number of Cutters of a PDC Bit
N	Rotary Speed, revolutions/s
D_b	Bit Diameter, m
F_{crL}	Critical WOB, N
K_{fL}	Friction Coefficient in Lubricated Conditions
$(FOI)_L$	Fold of Improvement, dimensionless
T_{dn}	Absolute Temperature in the Downstream, ^oC
T_{up}	Absolute Temperature in the Upstream, ^oC
p_{dn}	Absolute Pressure in the Downstream, psi
p_{up}	Absolute Pressure in the Upstream, psi
k	Specific Heat Ratio of Gas, dimensionless

T_{flC}	Fluid Temperature after Cooling, ^{o}C
T_{fl}	Fluid Temperature before Cooling, ^{o}C
μ	Friction Coefficient, dimensionless
w_V	Unit Weight of Vertical Section, lb/ft
w_C	Unit Weight of Curve Section, lb/ft
w_H	Unit Weight of Horizontal Section, lb/ft
H	Horizontal Length, ft
V	Vertical Length, ft
R	Radius of Curvature, ft
T	Hook Load, lb

CHAPTER 1: INTRODUCTION

1.1 History of Extended Reach Drilling

Extended reach wells (ERW) are special horizontal wells reaching the oil and gas reservoir sections far from the well location. Over the last two decades, the drilling of ERW has become a common practice in the oil and gas industry to improve field economics. Extended Reach Drilling (ERD) refers to drilling directional/horizontal wells beyond the routine capabilities of drill rigs and tools. This technique was initially developed in 1980s and rapidly evolved during the 1990s. Mueller *et al*. (1991) reported a well drilled to a total measured depth of 14,387 ft, with a horizontal departure of 12,740 ft at a true vertical depth of 4,420 ft. Eck-Olsen *et al*. (1993) described early strategies and techniques employed to extend the drilling reach in the Gullfaks field, offshore Norway. Emerging horizontal drilling techniques increased well inclination and extended the reach to 5 km. The early success achieved urged further consideration of extended reach drilling to as much as 10 km. Ryan *et al*. (1995) presented technological innovations that allowed for extending the step out record of 600 m to 7.8 km. Dolan *et al*. (1998) described the planning processes for spud, equipment, techniques and directional control used during the drilling a well with a total depth of 8,420 m (27,620 ft) and a horizontal step out of 7,372 m (24,190 ft) at a TVD of 28,66 m (9,400 ft). Naegel *et al*. (1998) reported a well by ERD with horizontal departure of 6.2 km at 1,700 m TVD. Elsborg *et al*. (2005) discussed the technologies required to drill and complete a 31,000 ft measured depth (MD) oil producer with ERD. McDermott *et al*. (2005) reported ERD and completion technologies successfully tested in a challenging remote Russian Far East location to prove feasibility of land based development for the offshore Chayvo field. Two ERD wells were drilled to measured depths of 9,375 m and 10,182 m. Horizontal displacements of the wells reached 8,419 m and 9,246 m at a true vertical depth (TVD) of 2,613 m. Algu *et al*. (2005) presented a case study of ERD in the GOM with water depths ranging from 2,000 ft to 4,000 ft. Five commercial pay sands were logged between 5,500 ft and 13,500 ft subsea. Woodfine (2008) discussed the challenges in drilling and completing an oil producer to 32,000 ft measured depth (MD).Walker (2008) reported the "Spanish Bay" well drilled from a production platform located offshore California in 1,075 ft of water, reached a total depth of 33,435 ft measured depth (MD)/7,663 ft true vertical depth (TVD) with 29,720 ft displacement. Walker (2009) reported technologies for increasing well reach to over 10.5 kilometers. Armstrong and Evans (2011) discussed the main engineering focus areas during planning and execution of an offshore well of a total depth of 37,165 ft measured depth (MD)/6,938 ft true vertical depth (TVD) with 33,682 ft of horizontal displacement (HD). Tskhadaya *et al*. (2013) presented scientific solutions regarding drilling of horizontal extended reach wells for the Arctic development. Much of attention was paid to load transfer from the well head to its bottom-hole. Their paper includes calculation of the well profile and load characteristics of the drilling complex for the well of 15 km and horizontal borehole depth of 1.5 km. The author proves perspectives of field's application and data about testing of down-hole drilling thrusting device. Chamat *et al*. (2014) reported ERD in shallow depth with TVD ranging from 1,500 ft to 2,500 ft.

Turner *et al*. (1989) described special difficulties in the early stage of ERD, including borehole stability, cuttings transport, data acquisition, drill string design, rig requirements, and well planning. Aarrestad (1994) addressed the various aspects of torque and drag problems encountered in drilling extended-reach wells. It discusses how to use torque and drag calculations and measurements to plan long-reach well profiles, to execute drilling operations that minimize torque and drag effects, to monitor hole cleaning, and to plan jarring operations. Payne *et al*. (1994) provided a review of the critical ERD technologies that increased profit margins on viable projects and made marginal prospects financially viable. Agawani *et al*. (1994) presented an algorithm, based on the steer ability of a bottom-hole assembly (BHA), to predict the complete geometry of the most suitable BHA to drill a given section of a directional well. Payne *et al*. (1995) summarized advances and emerging ERD technologies in the areas of wellbore stability, drilling fluids, drilling equipment, drilling systems, and tubular design and running. Nixon *et al*. (1996) described the strategies and techniques employed to solve the problems associated with excessive torque during offshore drilling of the Miller Field template wells. Krepp *et al*. (1996) chronicled the engineering designs and operational factors that made previously unreachable targets viable and substantially reduced the overall cost of ERD. Longwell and Seng (1996) presented the process employed to drill extended reach wells using conventional, readily available drilling technologies and contracted drilling equipment and services. Hill *et al*. (1996) presented a paper that covers designing and qualifying drill strings for extended reach wells. Judzis *et al*. (1997) presented a comprehensive set of ERD guidelines focusing on well design, planning, and operations. Payne and Bailey (1998) reported use of purpose-built drill pipes in substantial ERD to improve mud hydraulics and hole cleaning. Mason and Judzis (1998) presented survey about the limit of ERD based on field case studies. Cameron (2001) discussed the problems facing the operator in extended reach exploration and development drilling in the aspect of drilling fluids. Lumsden and Parker (2003) described ERD as good drilling practices used in North Sea. Rocha *et al*. (2003) discussed the effect of water depth on ERD in shallow water and deepwater. Suggett and Smith (2005) presented a paper addressing ERD with limit of rig capacity. Duan *et al*. (2006) presented their experimental investigations of transport behavior of small cuttings in ERD. Their results show significant differences in cuttings transport based on cuttings size. Smaller cuttings result in a higher cuttings concentration than larger cuttings in a horizontal annulus when tested with water. However, a lower concentration was achieved for smaller cuttings when polymers were added to the drilling fluid. Musaeus (2006) described some of the key drilling technologies used in the well construction of long reach and extended reach wells as part of the initial field development of six reservoirs from the Ringhorne platform. Bell *et al*. (2006) reported that a specific application consists of marrying single-diameter (expandable tubular) technology and ERD provided the foundation for a significant increase in the lateral reach of many extended-reach wellbores. Jellison *et al.* (2007) discussed drill string technologies involving advanced materials, ultra-high torque connection designs and other design considerations that are essential to achieve ERD targets. Hertfelder *et al*. (2008) reported ERD in environmentally sensitive offshore locations. Rubiandini (2008) summarized the design techniques for ERD in deep water. Samuel (2009) described a new well-path design that allows extending the reach of a well to a greater depth by reducing torque and drag through avoiding curvature and torsion discontinuities. Bjorkevoll *et al*. (2000) presented analyzed two North Sea extended reach wells in detail by comparing down hole pressure and temperature measurements with results from an advanced pressure and temperature simulator. Agbaji (2010) presented an algorithm that sets forth a design for a drilling program that is suitable to drill extended reach wells. Balandin (2010) discussed the option of using aluminum alloy drill pipe in ERD to reduce drag. Balandin (2010) discussed the use of

Buoyant Aluminum Drill Pipe (BADP) in ERD to reduce pipe weight and push the limit of ERD. Cheng *et al*. (2011) reported 4 extended-reach horizontal wells with the horizontal displacements larger than 4000m successfully completed by integrated application of pseudo-catenary trajectory design. Gui *et al*. (2012) presented a case study from offshore Vietnam where significant wellbore stability problems were found in drilling highly deviated and ERD wells from one platform. Hareland *et al*. (2012) presented their laboratory studies of no-particle drilling fluids is to reduce drag and thus extends horizontal distance in ERD. Vestavik *et al*. (2013) reported the potential application of Reelwell Drilling Method (RDM) to increase the envelope for ERD through torque and drag reduction, elimination of the dynamic Equivalent Circulating Density (ECD) gradient and optional hydraulic weight on bit. Tskhadaya *et al*. (2013) presented scientific solutions regarding drilling of horizontal extended reach wells for the Arctic development. The article included calculation of the well profile and load characteristics of the drilling complex for the well of 15 km depth. Newman *et al*. (2014) discussed ERD with coiled tubing (CT) where a limitation on the horizontal displacement occurs because of the frictional forces between the CT string and borehole while running in CT. This causes helical buckling and can lead to lockup of the CT, thereby limiting reach. Gupta *et al*. (2014) described the key challenges in ERD including high torque and drag, wellbore positioning in a thin oil column, wellbore stability, long horizontal completions, and down hole tool telemetry. The paper discussed the key well design features, equipment upgrades, and redesigns based on lessons learned.

1.2 Statement of Problems

Gas drilling is a technique that uses air, nitrogen, and natural gas as the circulating media to drill mining boreholes, geothermal fluid wells, and oil and natural gas recovery wells (Lyons *et al*., 2001). The drilling rate is usually over 10 times higher in gas drilling than that in liquid drilling (with water, mud, or oil). Gas drilling is especially attractive in drilling horizontal wells where high weight on bit (WOB) is not available due to the excessive friction between drill string and borehole wall. However, the performance of gas-drilling horizontals is highly inconsistent in many areas. The reason is believed to be inadequate optimization of drilling parameters due to limited knowledge of factors affecting rock failure in wells.

It is not understood how lubrication and cooling can affect the available weight on bit and horizontal reach. This study seeks answers to the following questions:

(1) How much will the lubrication by water-misting increase the permissible weight on bit?

(2) How is the permissible weight on bit affected by rock properties?

(3) How much will the bottom-hole cooling increase permissible weight on bit?

(4) How is the cooling effect affected by geothermal conditions?

(5) How can the additional Weight on Bit (WOB) be obtained from bottom hole assemblies?

1.3 Objectives of Study

The objectives of this study are to:

(1) Explore the potential of improving weight on bit by lubricating the bottom-hole;

(2) Determine the potential of improving weight on bit by cooling the bottom-hole;

(3) Develop a simple model and a rigorous model of the axial force transfer in fully stabilized Bottom-Hole Assembly (BHA) for optimizing weight on bit in gas drilling.

1.4 Significance of Study

A literature survey indicates that the major technical and operational challenges in ERD include high torque and drag, limit of hydraulics, pipe racking constraints, mud handling capacity, offshore logistics, and platform space limitations. The limit of drilling ERD comes from the excessive friction between drill string and borehole. The friction affects rig selection, drill string design, and casing design. The frictional drag that occurs in the upward motion of drill string has been well studied for rig selection. This frictional force that occurs in the downward motion of drill string controls axial force transfer and thus drill string stability. The frictional force in the downward motion of non-stabilized bottom-hole assembly (BHA) has been thoroughly studied for identifying “lock up” conditions which cause failure of drilling and completion operations. The frictional force in the downward motion of fully stabilized BHA determines the required drill collar weight and slack off of hook load during drilling. However, this has not been adequately studied and needs more investigation.

This study determines the potential of increasing weight on bit by lubrication and cooling of bottom-hole. Together with the axial force transfer model, the result will provide fundamentals for optimization of drilling parameters in ERD with gas.

CHAPTER 2: MATHEMATIC MODEL

2.1 Effects of Lubrication and Cooling on Weight on Bit

The first understanding of rock failure in wells was based on rock mechanics analysis in liquid drilling. Moore (1958) identified a number of factors affecting rock failure and thus rate of penetration (ROP). The first factor is the mechanical action of drill bit teeth that causes wedging, scraping and grinding, and crushing of rock. The second factor is the erosion of fluid jet action (Bourgoyne *et al.*, 1986). The third factor is the level of bottom-hole pressure relative to the confining stress in the rock (Murray and Cunningham, 1955; Cunningham and Fenink, 1959; Black and Green, 1978). It has been recognized that reducing bottom-hole pressure significantly increases ROP. This is due to the fact that the low-level bottom-hole pressure causes high-level of unbalance of stress in the rock, making the rock softer and easier to breakdown under the mechanical action of drill bit teeth. The bottom-hole pressure effect on rock failure seems to explain the high ROP in gas drilling (Sheffield and Sitzman, 1985; Li *et al.*, 2006; Wang *et al.*, 2008).But it does not explain all ROP behavior in gas drilling. For instance, a small amount of water (<3% in volume) is often added to the gas stream in gas drilling to reduce drill pipe vibration and cool drill bit teeth. Based on engineering calculations (Lyons *et al.*, 2009; Guo and Liu, 2011), this added water should not induce significant pressure increase at the bottom-hole. Bottom-hole pressure measurements also indicated that water contents of less than 3% in the gas streams did not cause significant pressure increase in boreholes (GRI, 1997). However, the investigators (Guo and Ghalambor, 2002; Zhang *et al.*, 2013) have reported that the water content caused a drop in ROP. Li *et al.* (2014) attributed this to the fourth factor affecting ROP, i.e., the temperature effect. Their explanation is that the water lubricates the contact area between the drill bit teeth and rock, reduces frictional heat at the rock surface and thus thermal stress in the rock which delays rock failure, resulting in low ROP.

The understanding of the temperature effect associated with the lubrication opens a new possibility of optimization of drilling parameters in gas drilling. Because the critical WOB and rotary speed increase as the rock temperature decreases (Glowka and Stone, 1985), the maximum permissible WOB and rotary speed can be elevated by lowering bottom-hole temperature. Considering the fact that ROP is a strong function of WOB and a weak function of rock temperature, reducing rock temperature and increasing WOB should improve ROP.

2.1.1 Optimization of PDC Bit Drilling

Glowka and Ortega (1984) are the pioneers in drilling optimization with polycrystalline diamond cutter (PDC) bits. They investigated the frictional heating and convective cooling of PDC during rock cutting. They concluded that very high thermal gradients can develop at the wear flat of PDC cutters and these probably contribute greatly to the heat cracking and chipping under drilling conditions. The mean wear flat temperature can be maintained below a maximum safe value of 750 ^{o}C (1,382 ^{o}F) only under conditions of low friction at the cutter/rock interface, regardless of the level of convective cooling. Glowka and Stone (1985) gave the following equation for calculating the critical weight on cutter (WOC):

$$W_{cr} = \frac{A_w}{\alpha f K_f v}\left(T_{cr} - T_{fl}\right) \tag{1}$$

where W_{cr} is the critical WOC in N, A_w is cutter wear flat area in cm^2, α is energy partitioning fraction, f is thermal response function, K_f is friction coefficient between cutter and rock, v is cutting speed in m/s, T_{cr} is critical cutter wear flat temperature in ^{o}C, and T_{fl} is the fluid temperature in ^{o}C. Considering 750 ^{o}C as the maximum safe value of cutter's temperature, the value of the critical cutter wear flat temperature of 350 ^{o}C by Stone (1986) gives a conservative estimate of the critical WOC.

The rate of penetration is proportional to the product of weight on bit (WOB) and rotary speed of drill bit. If the number of cutters of a PDC bit is n, the critical weight on bit (WOB) is expressed as:

$$F_{cr} = nW_{cr} \tag{2}$$

The cutter velocity may be conservatively calculated based on rotary speed for a cutter at the gauge diameter of bit:

$$v = \pi D_b N \tag{3}$$

where N is rotary speed in revolutions per second and D_b is bit diameter in meter.

Substituting Equations (2) and (3) into Equation (1) and rearranging the latter gives:

$$F_{cr} N = \frac{nA_w}{\pi \alpha f K_f D_b}\left(T_{cr} - T_{fl}\right) \tag{4}$$

For a given drill bit and rock, the values of the constants in this equation can be estimated based on the data provided by Glowka and Stone (1985). The optimum combination of weight on bit and rotary speed can be determined based on the friction coefficient and fluid temperature.

2.1.2 Effect of Lubrication on Drilling Optimization

Equation (4) indicates that lowering the friction coefficient will increase the product of the critical WOB and rotary speed. In conventional drilling operations where water-based mud is the circulating fluid, the friction coefficient of shale (and granite) is between 0.06 and 0.09; while in gas drilling operations where air or nitrogen is the circulating fluid, the friction coefficient is between 0.15 and 0.18.The friction coefficient of sandstone is between 0.03 and 0.05 in water drilling; while the friction coefficient, by Glowka and Stone (1985), is between 0.10 and 0.30 in gas drilling. If a small amount of water is injected with gas to the bottom-hole to lubricate the rock-cutter interface in gas drilling, less frictional heat will be generated when the same weight on bit is used. If the same critical temperature Tcr is allowed at the rock-cutter interface, the critical weight on bit will be elevated; and higher weight on bit and thus rate of penetration can be obtained. The combination of permissible WOB and rotary speed for lubricated condition is expressed as:

$$F_{cr\,L}N = \frac{nA_w}{\pi \alpha f K_{fL} D_b}\left(T_{cr} - T_{fl}\right) \tag{5}$$

Where F_{crL} is the critical WOB and K_{fL} is the friction coefficient in lubricated conditions. If the rotary speed is fixed, dividing Eq. (5) by Eq. (4) yields the fold of improvement in permissible WOB:

$$(FOI)_L = \frac{F_{cr\,L}}{F_{cr}} = \frac{K_f}{K_{fL}} \tag{6}$$

As observed by Glowka and Stone's (1985) investigation, the friction coefficients in water system is 2 to 3 times less than that in gas systems. It is therefore expected that the WOB and rate of penetration can be increased by 2 to 3 times if a small amount of water is injected to lubricate the gas drilling system. Because the reduction in friction is more significant in drilling sandstones than drilling shale, it is anticipated that the benefit of lubrication is more pronounced in drilling tight sand reservoirs than shale gas/oil reservoirs.

2.1.3 Effect of Gas Temperature on Drilling Optimization

It is logical to elevate the critical weight on bit by cooling down the bit cutters with drilling fluid. This is difficult to achieve in liquid drilling operations because the drilling fluid at bottom reaches a temperature near the geothermal temperature due to the heat transfer along the flow path. However, local cooling at bottom-hole is achievable in gas drilling operations by increasing pressure drop at the bit. When gas expands suddenly at the outlet of bit orifices, gas temperature drops due to Joule-Thomason effect. Assuming an isentropic process for an ideal gas flowing through bit orifices, the temperature at the orifice downstream can be predicted using the following equation (Guo and Ghalambor, 2012):

$$T_{dn} = T_{up}\left(\frac{p_{dn}}{p_{up}}\right)^{\frac{k-1}{k}} \tag{7}$$

where T_{dn} and T_{up} are the absolute temperatures in the downstream and upstream of bit orifices, respectively, p_{dn} and p_{up} are the absolute pressures in the downstream and upstream of bit orifices, respectively, and k is the specific heat ratio of gas. According to Guo and Liu (2011), for a gas with k = 1.3, if the near sonic flow condition is reached at pressure ratio of 0.54, Eq. (7) predicts the gas temperature at bottom-hole as follows:

$$\left(T_{flC} + 273.15\right) = \left(T_{flC} + 273.15\right)(0.54)^{(1.3-1)/1.3} \tag{8}$$

or

$$T_{flC} = 0.84T_{fl} - 44 \tag{9}$$

where T_{flC} is the fluid temperature in ^oC after cooling and T_{fl} is the fluid temperature in ^oC before cooling. Substituting Eq. (9) into Eq. (5) gives

$$F_{crC}N = \frac{nA_w}{\pi\alpha f K_f D_b}\left(T_{cr} - 0.84T_{fl} + 44\right) \tag{10}$$

where F_{crC} is the critical WOB in the cooled conditions. If the rotary speed is fixed, dividing Eq. (10) by Eq. (4) yields the fold of improvement in permissible WOB:

$$(FOI)_C = \frac{F_{crC}}{F_{cr}} = \frac{T_{cr} - 0.84T_{fl} + 44}{T_{cr} - T_{fl}} \tag{11}$$

Figure 1 shows a plot of fluid temperature before cooling versus fold of improvement in WOB after cooling. It is seen that gas cooling is more beneficial in drilling formations with high geothermal gradients such as deep gas reservoirs.

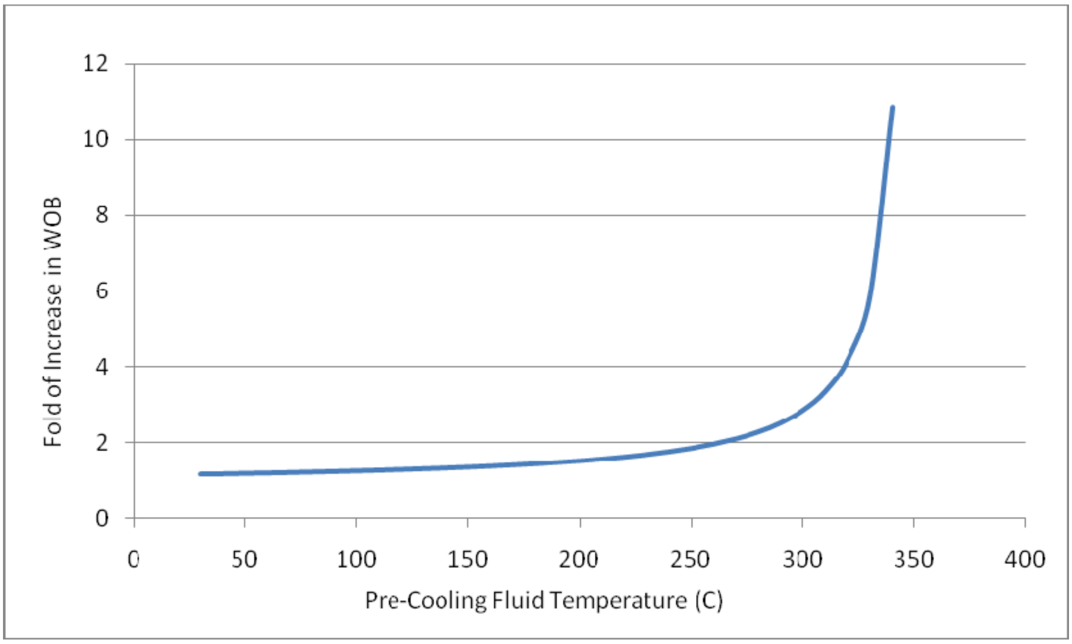

Figure 1: Relation between fluid temperature before cooling and fold of improvement in WOB after cooling

2.2 Availability of Weight on Bit

The derivation of mathematical models for horizontal displacement for horizontal wells should be based on four assumptions which are as follows:

1. The length of horizontal wellbore section is the limit of the length due to the borehole friction in the down-ward motion of work string.
2. Lockup of work string occurs in the pre-buckling condition.
3. The friction coefficient is constant over the entire length of string.
4. Dogleg is negligible along the well trajectory.

In addition, to simplify the analysis, the work string of horizontal well can be reduced to the key structure as in Figure 2.

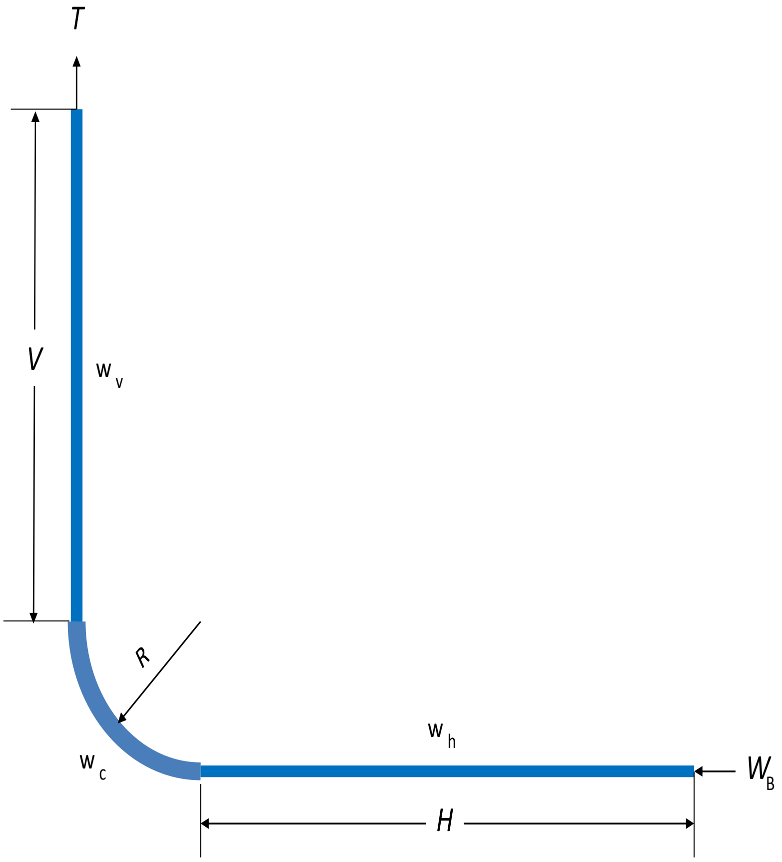

Figure 2: The key structure of horizontal well to simplify the analysis

2.2.1 Simplified Approach

A simplified method can be derived for quickly predicting the transfer of axial load in the work string. Based on the force analysis in the Figure 2, the driving force pushing the bottom-hole assembly (BHA) forward is the weight of string in the vertical section and the component of the weight of string in the axial direction:

$$\text{Driving Force} = w_V V - T + \int_0^{\pi/2} w_C R\cos\theta d\theta = w_V V - T + w_C R \tag{12}$$

No integration constant exists when the boundary is used.

The resisting force is from the frictional forces that occur in the curve and horizontal sections plus the force from the rock at the end of string (Weight on Bit). The axial force from the vertical section transfers directly to the horizontal section and the total resisting force can be expressed as:

$$\text{Resisting Force} = \mu \int_0^{\pi/2} w_C R \sin\theta d\theta + \mu\left(w_V V - T + w_H H\right) + W_B$$

$$= \mu\left(w_C R + w_V V - T + w_H H\right) + W_B \qquad (13)$$

No integration constant exists when the boundary is used. Under equilibrium conditions, the resisting force is equal to the driving force. Combining Eq. (12) with Eq. (13) yields:

$$\mu\left(w_C R + w_V V - T + w_H H\right) + W_B = w_V V - T + w_C R \qquad (14)$$

This equation can be used to estimate the limit length of horizontal wells:

$$\mu\left(w_C R + w_V V + w_H H\right) = w_V V + w_C R \qquad (15)$$

The Eq. (15) can be simplified and rearranged as:

$$H = \frac{\left(w_V V + w_C R\right)/\mu - w_V V - w_C R}{w_H}$$

$$= \left(\frac{1-\mu}{\mu}\right)\frac{w_V V + w_C R}{w_H} \qquad (16)$$

2.2.2 Approximation Approach

An approximation method for predicting the transfer of axial load in the work string can be derived based on statics. Consider an upper portion of the curve section as shown in Figure 3. The positive directions of x-axial and y-axial are presented.

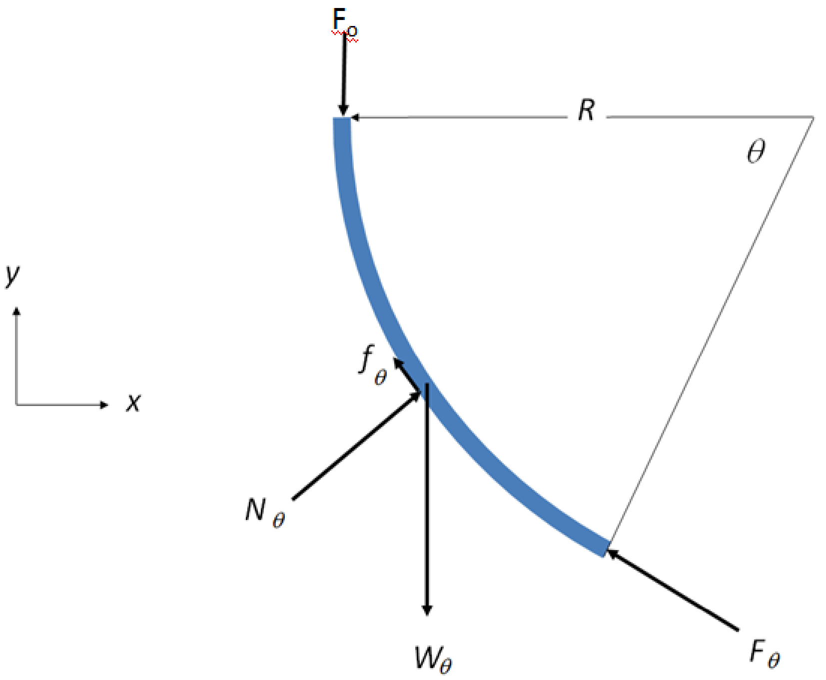

Figure 3: Simplified free-body diagram of a portion of the string in the curve section

In the horizontal direction:

$$\sum F_X = 0 \tag{17}$$

Eq. (17) can be extended as:

$$N_\theta \sin\frac{\theta}{2} - F_\theta \sin\theta - f_\theta \sin\frac{\theta}{2} = 0 \tag{18}$$

or

$$N_\theta\left(\cos\frac{\theta}{2}-\mu\sin\frac{\theta}{2}\right)-F_\theta\cos\theta=0 \tag{19}$$

In the vertical direction:

$$\sum F_y=0 \tag{20}$$

Based on the force analysis, this equation can be extended to:

$$N_\theta\cos\frac{\theta}{2}+F_\theta\cos\theta+f_\theta\cos\frac{\theta}{2}-W_\theta-F_0=0 \tag{21}$$

or

$$N_\theta\sin\frac{\theta}{2}+F_\theta\cos\theta+\mu N_\theta\cos\frac{\theta}{2}-\int_0^\theta w_C R d\theta-F_0=0 \tag{22}$$

which can be integrated as:

$$N_\theta\sin\frac{\theta}{2}(1+\mu)+F_\theta\cos\theta-w_C R\theta-F_0=0 \tag{23}$$

No integration constant exists when the boundary is used. Combining Eq. (19) and Eq. (23) gives the expression for the compressive force in the string at the point of inclination angle θ:

$$F_\theta=\frac{w_C R\theta+F_0}{\cos\theta+2\left(\frac{1+\mu}{1-\mu}\right)\cos^2\frac{\theta}{2}} \tag{24}$$

At the end of the curve section where $\theta={}^{\pi}\!/_{2}$, the compressive force takes the form of:

$$F_{\pi/2} = \frac{w_C R \frac{\pi}{2} + F_0}{\left(\frac{1+\mu}{1-\mu}\right)} = \frac{W_C + F_0}{\left(\frac{1+\mu}{1-\mu}\right)} \tag{25}$$

where W_C is the total weight of the curve section of string.

Applying the equilibrium condition to the horizontal section of string gives:

$$F_{\pi/2} - \mu w_H H - W_B = 0 \tag{26}$$

Substituting $F_0 = w_V V - T$ and Eq. (25) into Eq. (26) yields:

$$\frac{w_V V - T + W_C}{\left(\frac{1+\mu}{1-\mu}\right)} = \mu w_H H + W_B \tag{27}$$

This equation can used to estimate the horizontal well limit by setting T = 0 and $W_B = 0$:

$$H = \left(\frac{1-\mu}{1+\mu}\right)\frac{w_V V + W_C}{\mu w_H} \tag{28}$$

2.2.3 Rigorous Approach

A rigorous method for predicting the transfer of axial load in the work string can be derived based on calculus. Consider an element of the curve section with length $d_L = Rd\theta$ as shown in the Figure 4.

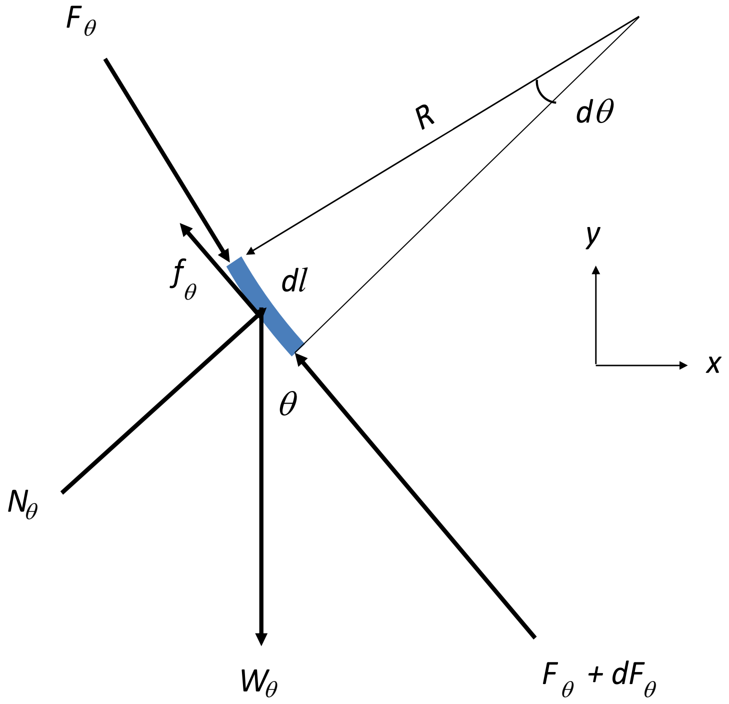

Figure 4: Free-body diagram of a portion of the string in the curve section

Force balance in the axial direction gives:

$$\sum F_a = 0 \tag{29}$$

This can be extended as:

$$df_\theta = W_\theta \cos\theta - f_\theta \tag{30}$$

where

$$W_\theta = w_C R d\theta \tag{31}$$

and,

$$f_\theta = \mu N_\theta = \mu W_\theta \sin\theta \tag{32}$$

Substituting Eq. (31) and Eq. (32) into Eq. (30) yields:

$$dF_\theta = w_C R(\cos\theta - \sin\theta)d\theta \tag{33}$$

Applying the boundary condition:

At $\theta = 0$,

$$F_\theta = F_0 \tag{34}$$

Integration of Eq. (33) takes the form of:

$$\int_{F_0}^{F_\theta} dF_\theta = \int_0^\theta w_C R(\cos\theta - \mu\sin\theta)d\theta \tag{35}$$

which gives:

$$F_\theta = F_0 + w_C R[\sin\theta - \mu(1-\cos\theta)] \tag{36}$$

No integration constant exists when the boundary is used.

At the end of the curve section where $\theta = {}^{\pi}\!/_{2}$, the compressive force takes the form of:

$$F_{\pi/2} = F_0 + w_C R(1-\mu) \tag{37}$$

Applying the equilibrium condition to the horizontal section of string gives:

$$F_{\pi/2} - \mu w_h H - W_B = 0 \tag{38}$$

Substituting $F_0 = w_V V - T$ and Eq. (37) into Eq. (38) yields:

$$H = \frac{w_V V - T + w_C R(1-\mu) - W_B}{\mu w_h} \tag{39}$$

This equation can be used to estimate the limit length of horizontal wells:

$$H = \frac{w_V V + w_C R(1-\mu)}{\mu w_H} \tag{40}$$

CHAPTER 3: MODEL COMPARISON

The three models of force transfer can be used to estimate the limit of horizontal displacement under the desired weight on bit and hook load. The limit of horizontal displacement can be expressed as follows:

For the Simplified Method,

$$H_S = \frac{(1-\mu)(w_V V - T + w_C R) - W_B}{\mu w_H} \tag{41}$$

For the Approximation Method,

$$H_A = \frac{\left(\frac{1-\mu}{1+\mu}\right)(w_V V - T + W_C) - W_B}{\mu w_H} \tag{42}$$

For the Rigorous Method,

$$H_R = \frac{w_V V - T + w_C R(1-\mu) - W_B}{\mu w_H} \tag{43}$$

Taking an example data set as follows:

w_C = 37 lb/ft;

V = 3000 ft;

w_V = 12.31 lb/ft;

R = 500 ft;

W_H = 8.81 lb/ft;

T = 30,000 lb;

WOB = 3000 lb.

Figure 5 shows the comparison of results given by the three models. From this comparison, it is noticed that the result from the Simplified Approach and that from the Rigorous Method are close in the high-friction region, while the result from the Approximation Method and that from the Rigorous Method are close in the low-friction region.

In field operations, the neutral point is usually kept at the top joint of drill collar, meaning that total vertical weight ($w_V V$) and the hook load (T) are approximately equal. The comparison plots for this situation are presented in Figure 6. It shows that the Simplified Method and the Rigorous Method yield the same result, while the Approximation Method gives optimistic result. The limit of horizontal displacement is calculated by the Rigorous Method in the Sensitivity Analysis of the next chapter.

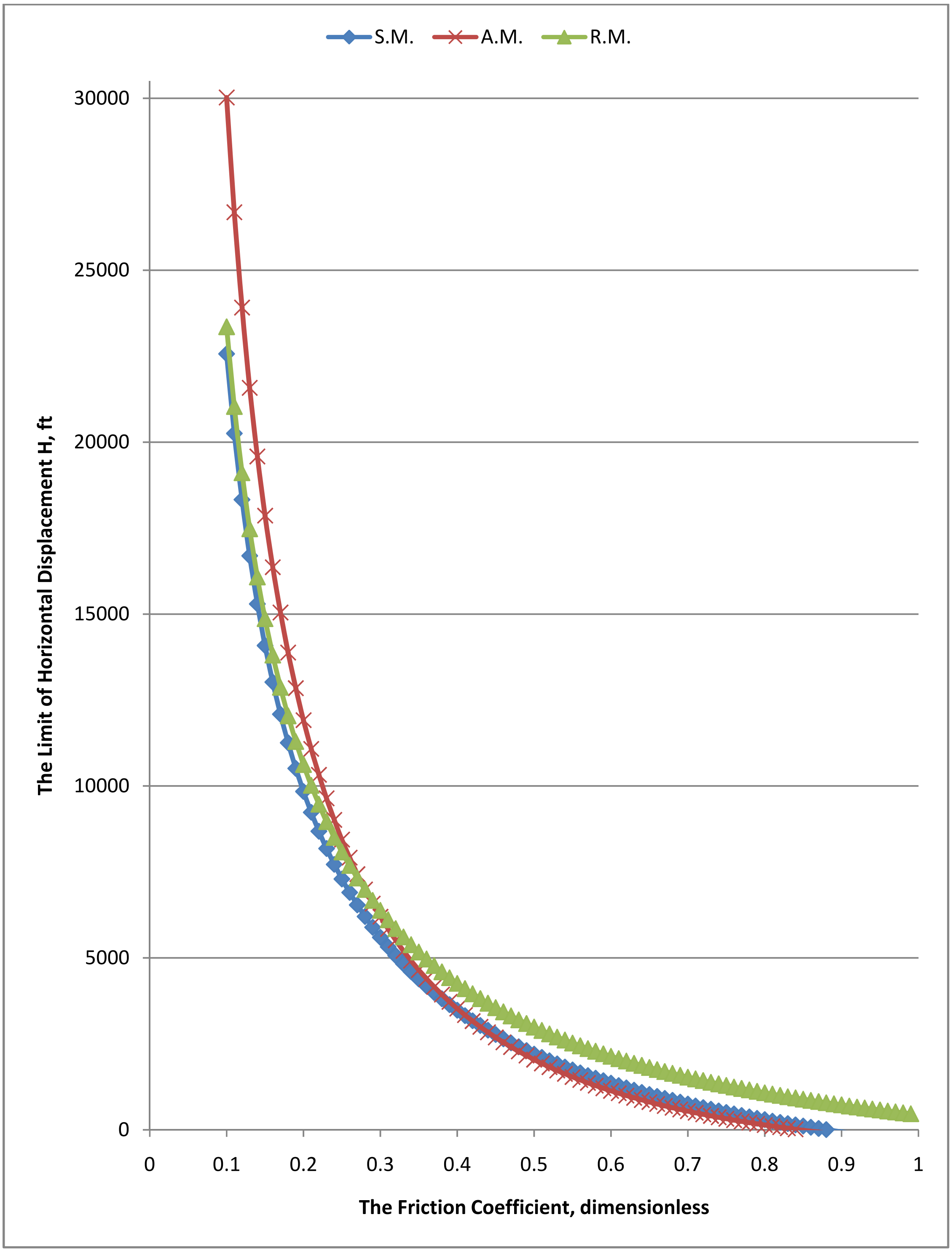

Figure 5: A comparison of three models with a typical data set with $w_V V \neq T$

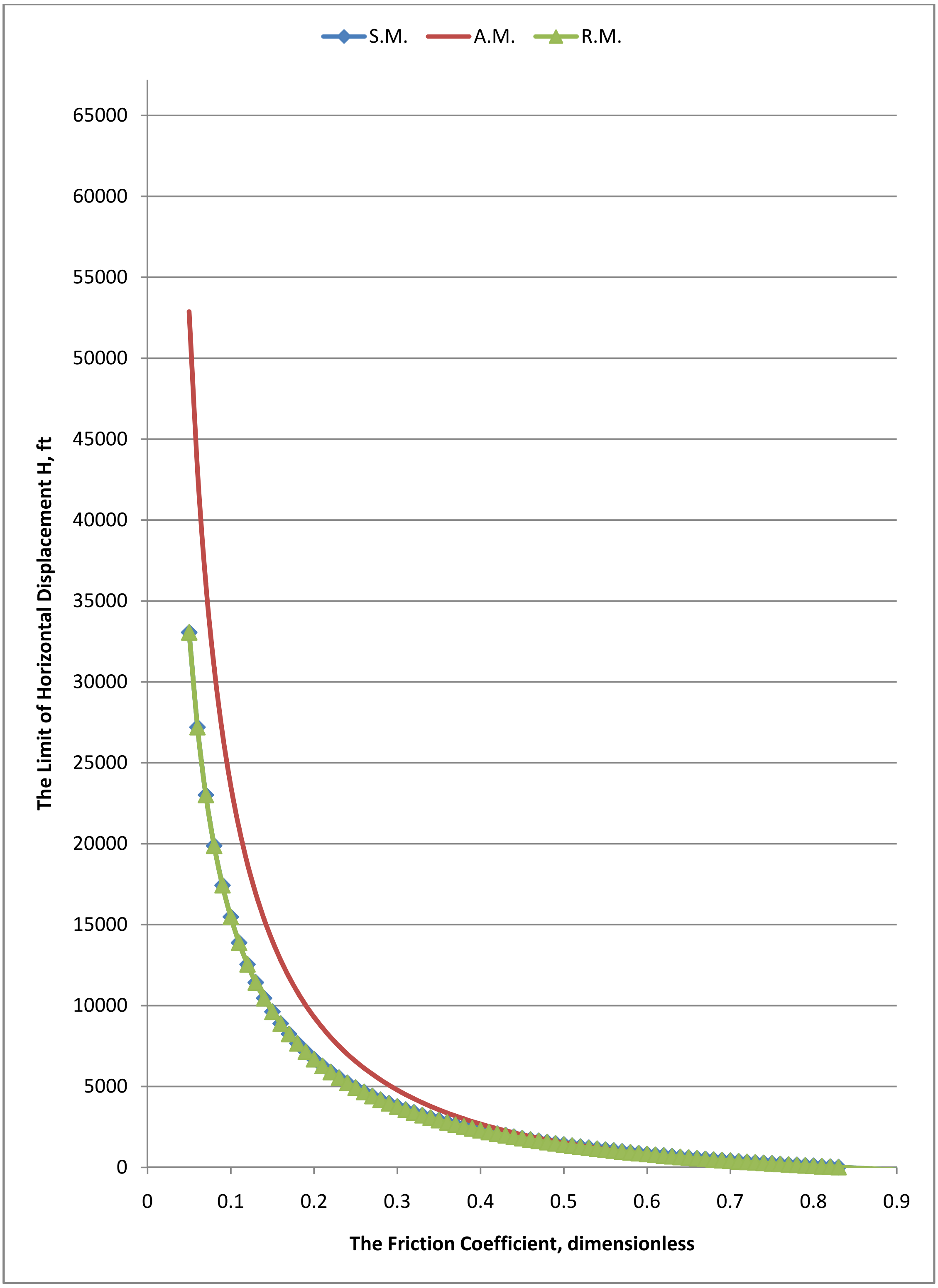

Figure 6: Estimations of the limit of horizontal displacement for $w_V V = T$

CHAPTER 4: SENSITIVITY ANALYSIS

As shown in Chapter 3, the Rigorous Method is derived based on force analysis to micro-elements. It has been shown that the Rigorous Method gives more conservative results than the other two methods in the practical range of friction coefficient (0.1 to 0.4). Thus this chapter presents sensitivity analysis focusing on the Rigorous Method and it shows how the parameters in the model affect the calculation result.

4.1 Effect of Bottom Hole Assembly (BHA)

Consider the three typical BHAs for horizontal drilling shown in Tables 1, 2, and 3. The recommended minimum WOBs of these three types of BHAs are all 1000 lb/in-diameter. To test the effects of BHA on the calculated limit of horizontal displacement, the minimum WOB and the parameters in the Table 4 were used in Eq. (42). The calculated values of the limit of horizontal displacement “H” are shown in the Figure 7. This figure indicates that the effect of BHA is very significant when the same WOB is used.

Table 1: The BHA-1 composition

Element	OD/ID (mm)	Length (m)
Bit	444.5	0.42
Check Valve	730/630	0.80
HWDP	127/76	196.20
STB	441/203/71	2.06
DC	203/71.4	28.12
XO	203/75	0.46
DC	165/71.4	55.94

Table 2: The BHA-2 composition

Element	OD/ID (mm)	Length (m)
Bit	311.1	0.35
XO	229/71.4	0.91
DP	127/76	139.50
DC	204/71.4	9.40
XO	203/71.4	0.78
STAB	308/71.4	2.05
XO	203/71.4	0.78
HWDP	127/76	56.20
XO	203/165/71.4	0.78
DC	165/71.4	82.69

Table 3: The BHA-3 composition

Element	OD/ID (mm)	Length (m)
Bit	215.9	0.24
Motor	172	8.32
Check-valve	172/72	0.59
Poppet Valve	172/72	0.89
MWD	172	3.27
5"NHWDP	127/76	9.28
5"HWDP	127/76	56.07
5"DP	127/109	519.27
5"HWDP	127/76	195.55
JAR	165/69	9.71
5"HWDP	127/76	56.29
DC	117/71.4	82.69

Table 4: The parameters for testing the effect of BHA

	Parameter	Value	Unit
BHA-1	w_C	112.20	lb/ft
	R	300.00	ft
	w_H	49.30	lb/ft
	μ	0.30	
	WOB min	1000.00	lb/in
		17500.00	lb
BHA-2	w_C	98.70	lb/ft
	R	450.00	ft
	w_H	32.40	lb/ft
	μ	0.26	
	WOB min	1000.00	lb/in
		12000.00	lb
BHA-3	w_C	43.60	lb/ft
	R	560.00	ft
	w_H	30.60	lb/ft
	μ	0.20	
	WOB min	1000.00	lb/in
		8500.00	lb

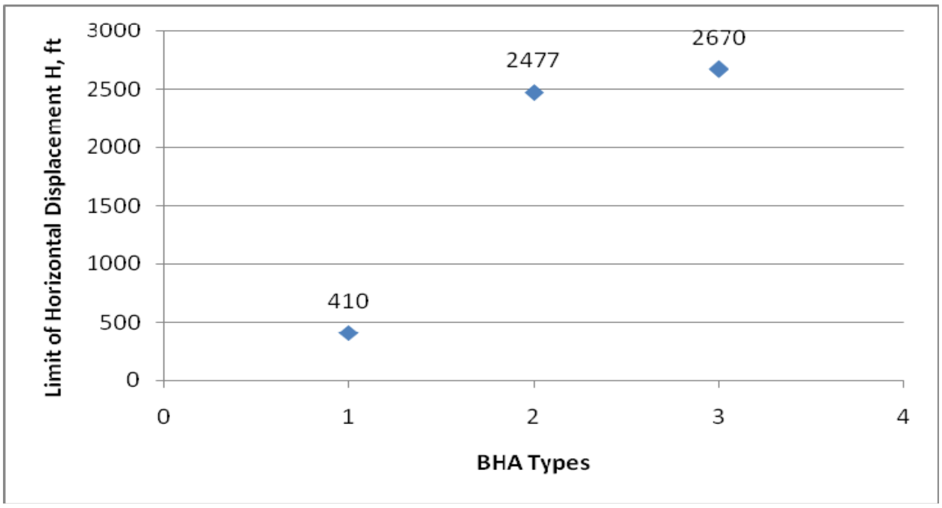

Figure 7: The calculated limit of horizontal displacement with different BHAs.

4.2 Effect of Hole Curvature

Hole curvature is a key factor in horizontal drilling. Its effect on the limit of horizontal displacement H is demonstrated in this section. Using the radius of hole curvature from 500 ft to 2000 ft in the previous example, the maximum achievable horizontal displacements were calculated and are shown in the Figure 8.

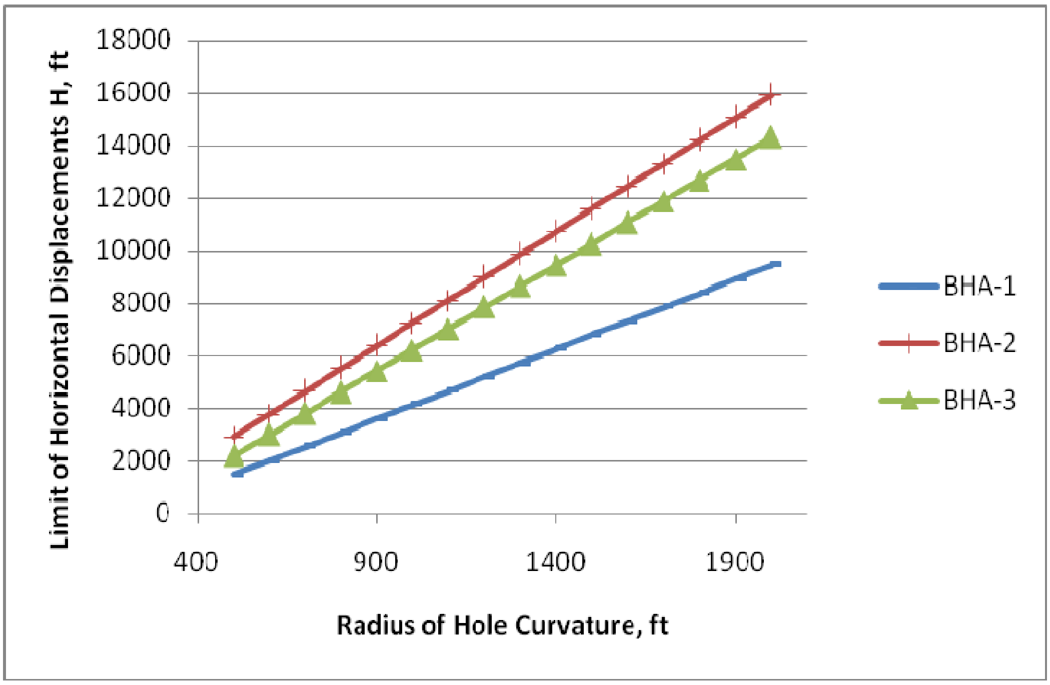

Figure 8: The effect of hole curvature on H

As shown in Figure 8, increasing radius of curvature will linearly improve the limit of horizontal displacement. This is because the weight of pipe in the curve section can provide more driving force to overcome the friction in the horizontal section. Of course, the improvement also depends on the size of BHA.

4.3 Effect of Friction Coefficient

The friction force is the major resistant force in horizontal drilling that determines the limit of horizontal displacement. In fact, the friction force is the key factor controlling the success of Extended Reach Drilling (ERD). Using the data for the three BHA’s and friction coefficient from 0.1 to 0.6, H-values were calculated and plotted in Figure 9. This figure shows that the limit of horizontal displacement drops sharply in the low-friction region as the friction coefficient increases. Therefore, reducing friction coefficient can significantly increase the limit of horizontal displacement, especially in low-friction systems. When the friction coefficient, μ, is lower than 0.25, the limit of horizontal displacement is very sensitive to the change of friction coefficient. When the friction coefficient μ is higher than 0.30, the influence of the friction coefficient is low. The friction coefficient can be reduced from 0.4 to 0.2 by water-misting in gas drilling operations.

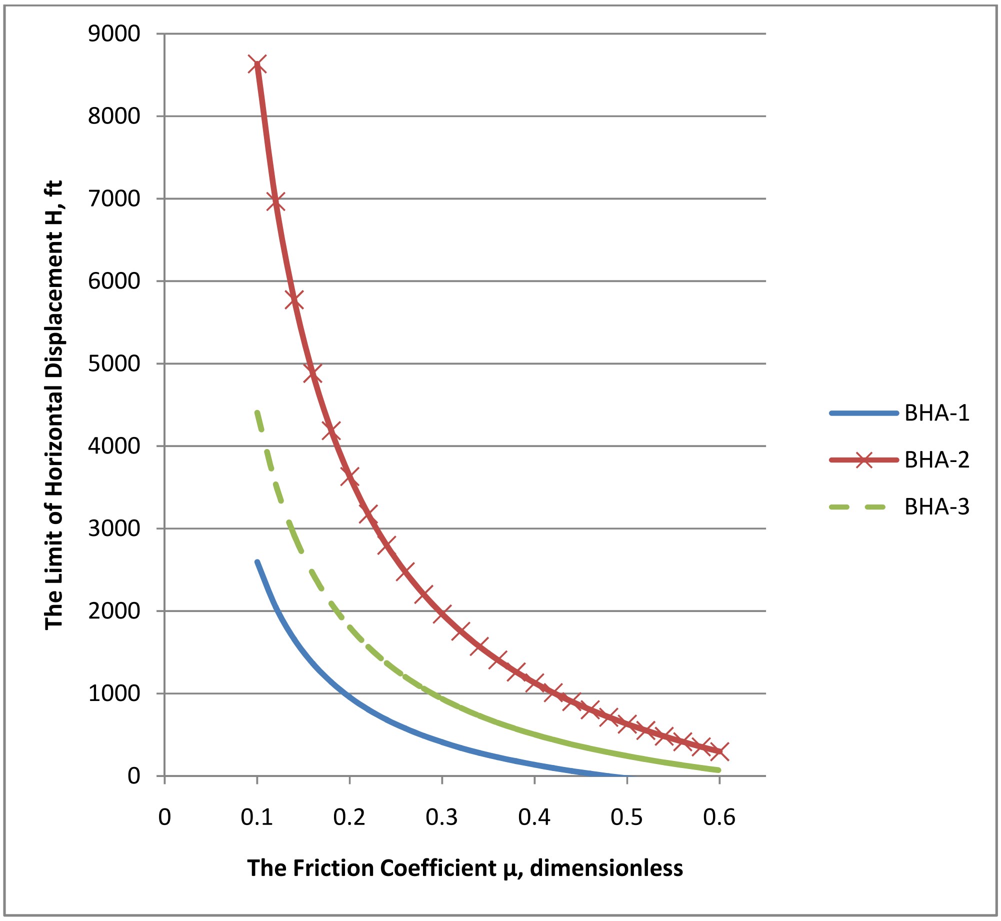

Figure 9: The effect of friction coefficient on H

4.4 Sensitivity Analysis

A sensitivity analysis was carried out to compare the relative importance of parameters affecting the limit of horizontal displacement using a cross-point plot. The base line data are presented in Table 5. The Parameter Normalization Ratio is defined as the value of the parameter divided by the base value of the parameter in Table 5. The result is shown in Figure 10. This figure demonstrates that the limit of horizontal displacement is sensitive to the parameters in the following decreasing order:

(1) Friction coefficient

(2) Unit weight of pipe in the horizontal section

(3) Unit weight of pipe in the curve section, and

(4) Weight on bit.

The friction coefficient is definitely the first parameter to minimize by water-misting in gas drilling. The weight on bit is determined by the bit selected and the requirement for rate of penetration. The unit weight of pipe in the horizontal section should be minimized if possible. The unit weight of pipe in the curve section should be increased to reach the desired horizontal displacement.

Table 5: The basic data set for the sensitivity analysis

Parameter	Value	Unit
μ	0.4	
w_V	14.0	lb/ft
V	3000.0	ft
w_C	25.0	lb/ft
R	1000.0	ft
w_H	10.0	lb/ft
T	30,000.0	lb
WOB	3000.0	lb

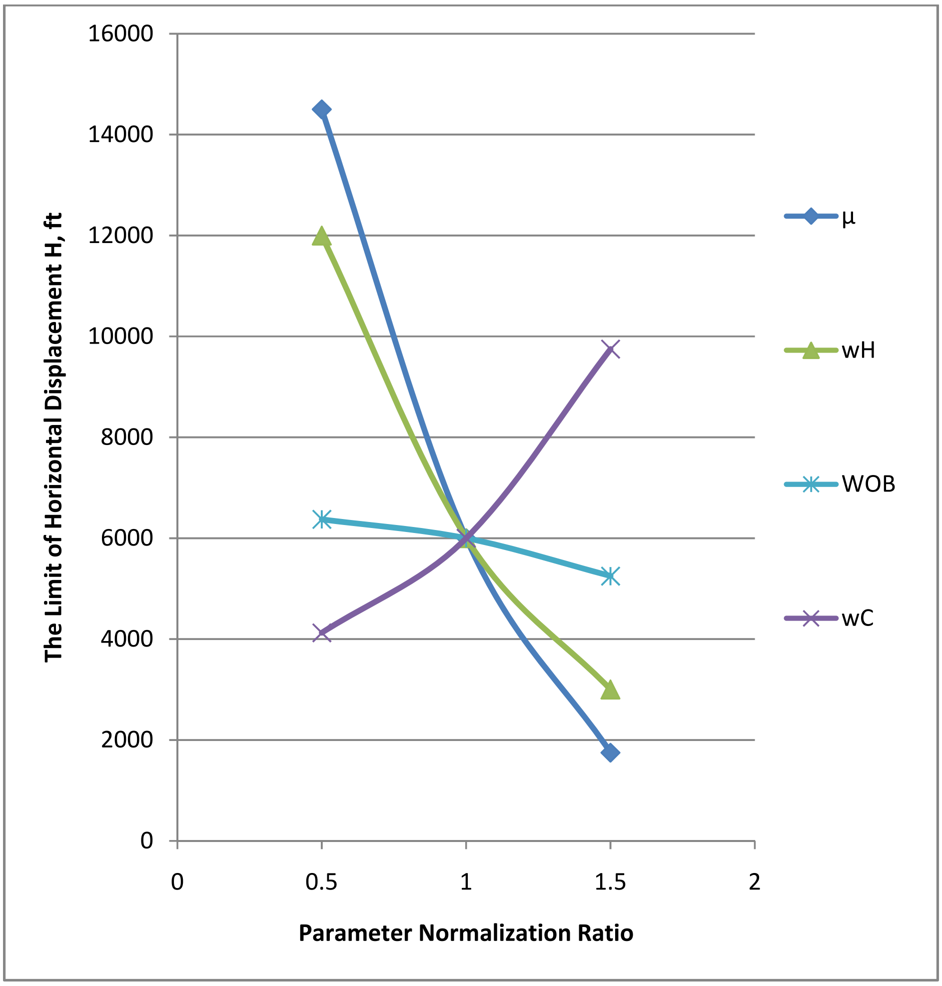

Figure 10: The sensitivity analysis with normalized parameters

CHAPTER 5: CONCLUSIONS

The following conclusions were made from this study:

1. Lubrication of bottom hole with water can significantly increase the maximum permissible WOB. This effect is more pronounced in drilling tight sands than shales with gas.
2. Cooling bottom hole with gas expansion after bit nozzles can greatly increase the maximum permissible WOB in drilling formations with geothermal temperatures above 200 ^oC.
3. Three mathematical methods have been developed for calculating the limit of horizontal displacement in extended drilling with gas. The Rigorous Method is recommended because it gives conservative result.
4. Among several factors affecting the ERD with gas, friction coefficient and the weight of pipe in the horizontal section are the two controlling factors. Adequate weight of BHA in the curve section should be used to overcome the friction.

The following practices are recommended:

1. Use water-misting in gas drilling to liberate and increase WOB;
2. Use small bit nozzle to cause bottom cooling to elevate the limit of WOB;
3. Use light pipes in the horizontal section to increase the limit of the ERD.

Future studies should focus on the following subjects:

1. Optimization of BHA in slant holes to maximize driving forces and minimize resistant forces due to friction;

(2) Optimization of gas injection to clean the hole to reduce friction and minimize gas drilling problems.

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ABSTRACT

The limit of drilling ERD comes from the excessive friction between the drill string and borehole. This study investigates the potential of increasing the limit of horizontal displacement through optimization of drilling fluid and bottom hole assemblies. We conclude that lubricating bottom hole with water can significantly increase the maximum permissible WOB. This effect is more pronounced in drilling tight sands than shales with gas. Cooling the bottom hole with gas expansion after bit nozzles can greatly increase the maximum permissible WOB in drilling formations with geothermal temperatures above 200 ^{o}C. Three mathematical methods have been developed for calculating the limit of horizontal displacement in extended drilling with gas. The Rigorous Method is recommended because it gives conservative result. Among several factors affecting the ERD with gas, friction coefficient and the weight of pipe in the horizontal section are the two controlling factors. Adequate weight of BHA in the curve section should be used to overcome the friction.

BIOGRAPHICAL SKETCH

Jinze Song was born on December 06, 1988, in Daqing, China to Chuanxiu Song and Xiurong Deng. In 2007, he was admitted to the China University of Petroleum. He earned a Bachelor of Science degree in Geophysics Engineering in 2011. He was admitted to the Graduate School at the University of Louisiana at Lafayette where he earned a Master of Science degree in Petroleum Engineering in Fall 2014.