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Finding the Optimum BHA through Data Analytics & Modeling

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Abstract

Drilling unconventional wells efficiently and smoothly in one run with only one BHA can be very challenging, as the behavior of a conventional BHA can often seem erratic and inconsistent. It is common for two similar BHAs drilling two wells on the same pad and same formation to have opposite behavior. This leads the engineer to blame a set of variables such as formation, toolface control, weak motor, or hole overgauge to name a few, often with no evidence other than gut feeling. With so many variables that need to be considered, a methodology that uses a physical model to determine the BHA behavior and its sensitivity to the variables is proposed. This methodology will be used to analyze a BHA for two cases; a curve and lateral section.

The method combines drilling data and offset wells analysis coupled to a rock-bit-BHA model to calculate and calibrate actual build and turn rates. Calibration is essential to define some of the variables that might not be easily known or determined such as hole over gauge and bit steerability. Once a good agreement is reached, a standard BHA is designed based off the BHAs used in the offset wells. A sensitivity analysis is then performed on this standard BHA to determine the effect of each component on the behavior and to modify the BHA to obtain an optimized BHA to be used to drill the next well, saving time and money compared to the classic methodology of trial and error.

Introduction

Understanding the directional behavior of a drilling system is key for drilling a well successfully but can often be challenging due to uncertain downhole events. One can prepare for such events by anticipating certain conditions and analyzing the prediction using a physical based BHA model. Certain parameters, such as hole overgauge (OVG), are very influential to downhole interactions which can cause a BHA to deflect in undesirable ways. Other parameters to consider are bit steerability (side-cutting ability of the bit) and slide efficiency with an emphasis on actual tool face orientation (TFO) data. However, these parameters are sometimes overlooked and not a priority measurement on most wells, making a methodology to analyze this more valuable.

Using bit and BHA physical based models have proven to be effective for pre & post analysis. Combining a BHA model[1] with a detailed bit/formation model can maximize an engineer's full understanding of the interaction between the rock, the bit and the BHA. A methodology proposed in this paper reveals an effective way to analyze post run data to understand why directional systems react certain ways in typical unconventional wells. Using post analysis data to understand these effects are becoming common forms of lessons learned which are then used for future BHA designs which have the potential for savings across numerous areas.

Modeling Background

The methodology proposed in the paper defines an advanced BHA directional response model which incorporates the following:

- The Bit - A detailed bit model focusing on the steerability and walk tendency of the bit[2,3]
- The Rock - Formation hardness[4]
- The BHA - A powerful 3D BHA/hole interaction model[1,5]

Bit Model

The bit's directional behavior is described by two main parameters; the bit steerability and walk angle (Figure 1). Bit steerability can be defined as the ratio of lateral to axial drillability. It corresponds to the side cutting ability of the bit, to initiate a deviation, given a side force applied on the bit. The bit steerability is a ratio that ranges generally from 2% for very low steerable bit (long gage) to about 50% for short gage bit drilling in a soft formation. This bit steerability affects mainly the build/drop rates of any directional system (steerable mud motor, rotary BHA, Rotary Steerable Systems push/point). The walk angle corresponds to the angle between the lateral displacement of the bit and the direction of this side force applied by the BHA. This angle (negative for left tendency bits, and positive for right tendency bits) ranges generally from -5deg. to -25deg. depending mainly on the coefficient of friction between the gage and the rock formation. There are several factors that can impact these 2 parameters (bit steerability and walk) such as the overall cutting structure of the bit (profile, back rake of the cutters), gauge length and characteristics[2,3,5], trimmers, as well as the friction of the wellbore. All these factors are considered when determining the overall steerability and walk of the bit. The bit specifications sheet has generally the necessary information to calculate, with a reasonable degree of accuracy these 2 parameters.

Formation

Formation hardness is often overlooked when evaluating the directional response of a system mainly due to its complexity and often changing atmosphere. The bit model in this study considers the Unconfined Compressive Strength (UCS) to evaluate the overall bit steerability. Calibrating the bit steerability to certain formations (sands, shales, limestone) plays a huge role when understanding why certain build/turn rates occur. We observe generally that the bit steerability decreases with harder rock formations (Figure 2). The same bit and same BHA in 3 different rock formations will generate 3 different build rates (all other things being equal).

BHA Model

The BHA model[1] proposed in this study derives the directional response by evaluating the contact forces along the BHA (bit, stabilizers, kick-pad, drill collar, etc…), resulting to a deflection along the string, tilt and side force at the bit. Figure 3 shows the basic schematics of the coupling between the bit model and the BHA model to calculate the drilling direction taken by the system. This model was developed over multiple years of research and extensive laboratory/field validation in numerous wells. The model can handle systems from the conventional steerable mud motor and variable gauge stabilizer (VGS) to a push/point Rotary Steerable System (RSS). Figure 4 shows an example of analysis performed at the design stage to select the right bend angle for a given application (6 3/4in. steerable mud motor example). The plot shows the build and turn rate calculated for several tool face orientations and different bend angles (1.5 to 2.5deg.), assuming no hole overgauge. This graph is also interesting to estimate the overall steerability of the full system. For example, with 1.5deg., one can build at a maximum rate of 7deg./100ft, drop up to 8.5deg./100ft, and turn to the left or right with about 11deg./100ft. This sensitivity analysis should be conducted at different inclinations, WOB and hole overgauge to estimate the full response of the system under varying parameters. Figure 5 shows another example where the bit steerability and hole overgauge are varied (sliding mode, TFO =0deg.). As a global trend one observes that the build rate of the system decreases with hole overgauge and bit steerability. If the bit steerability increases, it means that the bit has a higher side-cutting ability (shorter gage pad). As the main deviation mechanism for a steerable mud motor is based on the tilt of the bit (one points the bit is a given and desired direction), one does not want the bit to be influenced by the side force, and a long gage is generally preferred. Also, it’s interesting to notice a significant drop in build rates with overgauge above 0.3in. About 20% of the building capability of the system is diminished going from 0.3in. to 0.5in. hole overgauge.

Data Quality

One of the biggest challenges the industry faces is data management and quality control. For decades, standard operating procedures & methodologies have been put in place for data management yet till today, engineers battle the time-consuming task of gathering/processing/QA-QC information from the field. In order to ensure the absolute maximum benefit from a data driven analysis, information must be accurate and organized. We have chosen in the present paper to highlight the importance of 2 parameters; weight-on-bit (WOB) and tool face orientation (TFO). Indeed, if TFO and/or WOB are inaccurate or just wrong, obviously the build/turn rate calculated by the rock-bit-BHA model will be wrong. As we’ll see later, a 10-20 deg. TFO error can make a big difference in terms of build/drop rate, and the WOB also affects the deflection of the BHA and therefore the drilling direction taken by the system.

Weight-on-Bit

The pre and post-analysis process effectively considers the effect of WOB on the system, as the deflection and contact points changes according to the level of compression. This data is taken directly from the Electronic Drilling Recorder (EDR) but corresponds generally to the “surface” WOB and sometimes is not always zeroed out by the driller. There are tools available in the market to measure the actual downhole WOB with sensors but are not used on all wells. This is mostly due to functionality and cost but from a data analytics standpoint, the quality of the analysis would increase dramatically if downhole data were available.

Slide Sheet vs TFO Log

Another important parameter to consider in terms of data quality is TFO. The objective here would either be taking the slide sheet from the Directional Driller (DD) or the actual TFO data from the Measurement While Drilling (MWD) tool accessible generally via the EDR. Figure 6 shows an example of discrepancies sometimes observed when comparing the same information from 2 different sources. Not only the difference of 16 deg. in the TFO will affect the global build/drop rate prediction over that section, but the variations on a short scale will also impact the tortuosity of the wellbore.

The main task of a DD while steering a well is document the slide footage per stand, with an average TFO estimation over a certain distance, to evaluate the motor yield. This document is referred to as a slide sheet. Unfortunately, the precision of a slide sheet can be of somewhat lower accuracy when describing steering events, especially when analyzing the information from a data analytics standpoint. One can imagine the difficulty in believing the common phrase “Slide 100% high side for 90 feet”. For this to happen, the toolface must be aligned high side to exactly 0 degrees for the entire stand. This is not entirely accurate due to reactive torque and common deflections that occur from the rock and bit. For example, the case study examined shows the TFO data for the slide interval from 10,860 ft to 10,970 ft (Figure 7). The slide sheet recorded from the DD indicated 100% high side for the duration of the stand but as one can see in the plot, there were many deflections and tool face control were quite difficult. There were times when the TFO was positioned at 80 degrees (left and right) from the target and from a steering perspective, the building capabilities are diminished until the orientation is corrected back to high side.

Slide Efficiency

There are 2 key elements to plan for when considering motor yields from a steerable mud motor– slide/rotate percentage and slide efficiency. Sliding 100% of the time in the curve does not pose the best scenario for hole cleaning or high rate of penetration, so some rotation might be preferred. Some operators like to slide 100% of the curve (which is the case for part of this study) for overall wellbore condition to avoid the slide-rotate pattern that generates high local dog leg[6]. For the sake of finding an optimum BHA for build capabilities, some trend analysis should be carried out from offset wells or formation tendencies and calculated beforehand. It is important to anticipate tool face control for due to reactive torque and BHA not reacting to certain formation as planned.

Figure 8 shows an example of build and turn rate calculated for a steerable mud motor for several tool face orientations (sliding mode). One notices that if the tool face goes away from the target TFO (0in. our example), the build rate can change from 14.5deg./100ft (TFO=0 deg.) to about 12deg./100ft if the TFO is just off by +/- 30deg. (TFO= 30 or 330deg.). As keeping the TFO exactly on the target is extremely difficult, one might consider at the planning stage a margin of error in case the DD is having a very hard time staying in the green zone.

Case Study

Plan

The main objective for most drilling companies is drill the curve and lateral in one run with minimum sliding in the lateral. To achieve this, a BHA should be properly designed to reach the doglegs required in the curve and have a neutral rotating tendency in the lateral. Several aspects need to be considered when designing a BHA such as bit, slick/stabilized motor, motor bend angle, motor collar OD, bit to bend distance, stabilizer placement and diameter. For this study, we chose to examine a BHA with an 8 ¾in. 7 bladed PDC bit (2in. gage pad), 6 ¾in. stabilized steerable mud motor with a 2.38deg. bend, 8in. stabilizer located above the motor, MWD and flex collar (see Table 1). The plan required the following:

- Average 12 deg/100ft doglegs in the curve
- Kicking off from vertical with some rotation required for first 30 deg. of inclination (80% Slide, 20% Rotate) in Formation XXX
- 100% slide in the Formation YYY until landing the curve
- 10,000ft lateral with minimum sliding

The calculated bit steerability is 20% and the walk angle -15 deg. assuming a coefficient of friction of 0.3 and a UCS of 9000psi.

Post Analysis

Curve

The first step to performing a post analysis study on a BHA is importing all the BHAs, runs, and drilling mechanics data that is available into the software and then calibrate the hole overgauge to match actual tendency with model prediction. The motor was yielding about 10deg./100ft doglegs in the first section of the curve (formation XXX) and about 14deg./100ft doglegs for the remainder. From the start, one can imagine the difficulty in landing a curve with these motor yields. Calibration suggested 3/4in. hole overgauge in formation XXX and a 1/4in. in formation YYY (Figure 9).

When examining the BHA contact points in the curve with 0.25in. and 0.75in. hole overgauge, we notice that the first contact point after the bit with 0.25in. hole overgauge is directly on the sleeve, whereas when the hole has 0.75in. hole overgauge the first contact point after the bit has shifted to the motor bend and no contact is observed on the sleeve (see Figure 10).

Lateral

The plan called for about 10,000ft of lateral, so having a neutral BHA was very important in terms of avoiding a tortuous wellbore and, not to mention, the overall time savings with minimum directional work. One can imagine the effects of a large bend on a motor rotating continuously in the lateral creating a hole size much bigger than anticipated and associated fatigue on the mud motor[7]. The calibration in the post analysis suggested about 0.65in. of hole overgauge to have a reasonable agreement with actual build rate (Figure 11). Despite this quite large hole overgauge, the BHA maintained a neutral tendency with 20% sliding for the duration of the lateral. If an operator can cut this slide time down to 10%, the benefits on paper would be noteworthy.

This improvement can be achieved in trying to make this BHA less sensitive to the WOB in rotating mode. Figure 12 shows the rotating build rate of the BHA at 90 deg. inclination at several WOB and bit steerability. One observes that the BHA can be neutral for specific parameters. For example, at a very low bit steerability (long gage), this BHA is very sensitive to the WOB. Indeed, the BHA can drop at 5klbs WOB but build at 25klbs WOB, making this BHA not very controllable. However, one notices that around 15% bit steerability, the WOB effect is less and the build/drop rate is within +/- 0.20 deg/100ft. One suggestion to improve this BHA was then to increase slightly the gage length (to reduce the bit steerability). It's worth mentioning that this is not the only way to make a BHA neutral, as stabilizer placement, sleeve OD, bit-to-bend distance play also a great role in the directional behavior of the BHA.

Conclusions

A physical-based BHA model has been used to optimize and understand the directional behavior of a steerable mud motor drilling a curve and lateral section of an unconventional well. The BHA model includes a PDC bit model that interacts with the rock formation to quantify the steerability and walk tendency of the bit. We have also shown that data quality is of tremendous importance to provide reliable inputs for the BHA model, as some parameters (WOB, TFO) have a significant influence on the build/turn rate prediction. A good knowledge of the tool face orientation for example is key to be able to reproduce properly the trajectory using the BHA model. The methodology described in the paper is mainly based on a post-analysis of the performance of a BHA via a calibration of the hole overgauge. This methodology has been used to optimize an existing BHA design to be more predictive for the next well, enabling to speed up considerably the learning curve instead of using the trial-and-error method.

Nomenclature

BHA = Bottom Hole Assembly
WOB = Weight-on-Bit
TFO = Tool Face Orientation
OVG = Overgauge
DD = Directional Driller
EDR = Electronic Drilling Recorder
MWD = Measurements While Drilling
RSS = Rotary Steerable System
VGS = Variable Gauge Stabilizer

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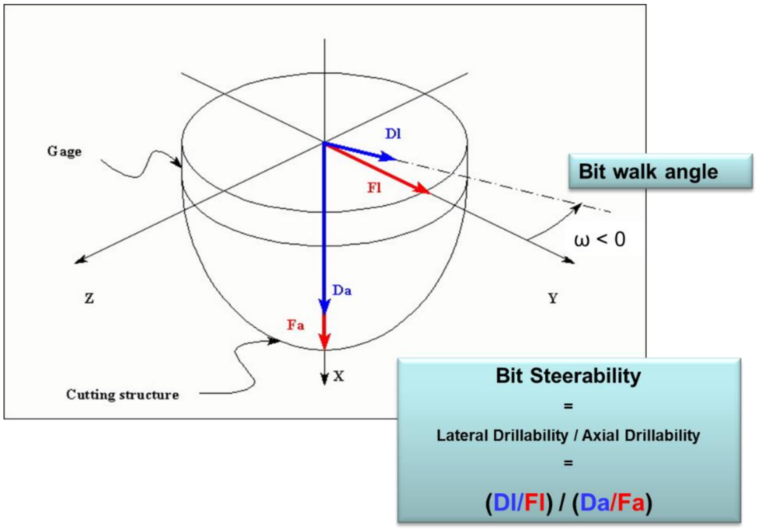


Figure 1: Definition of bit steerability & bit walk angle

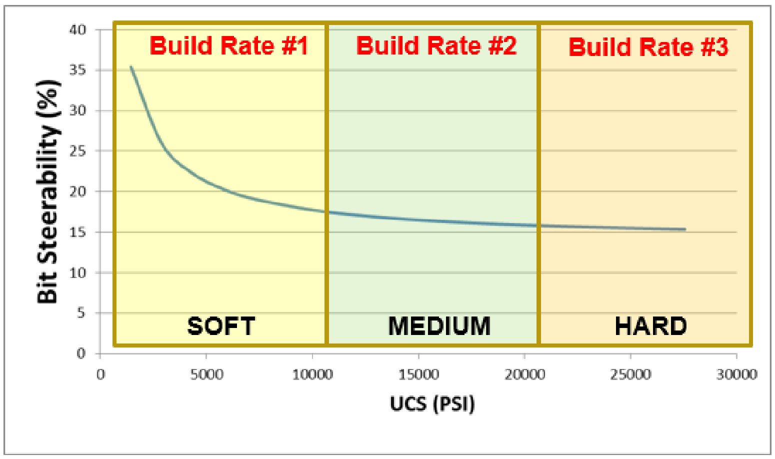


Figure 2: Example of UCS effect on bit steerability

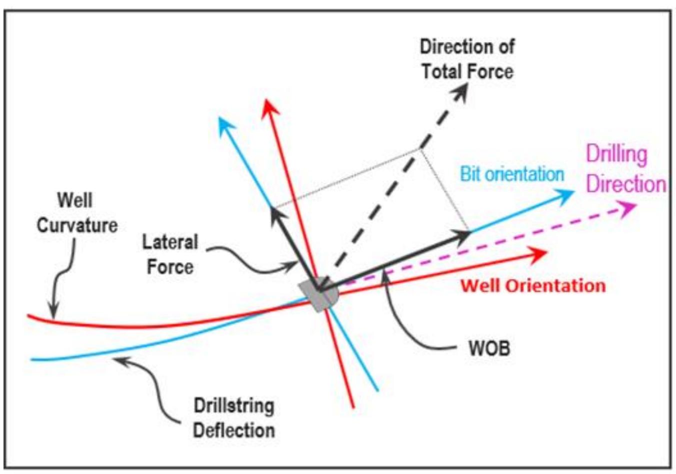


Figure 3: Principle of the coupling between the Bit & BHA Model

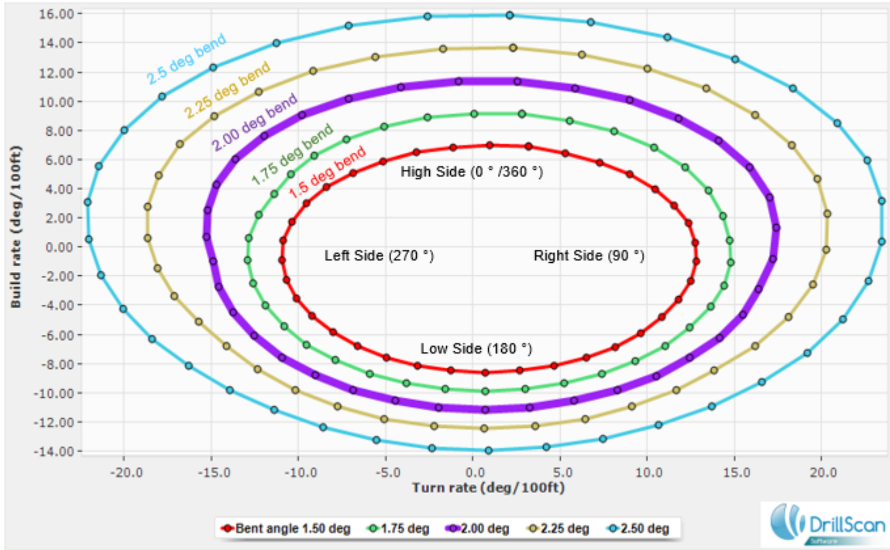


Figure 4: Sensitivity Analysis: Build/Turn rates for different Bend Angles and TFO

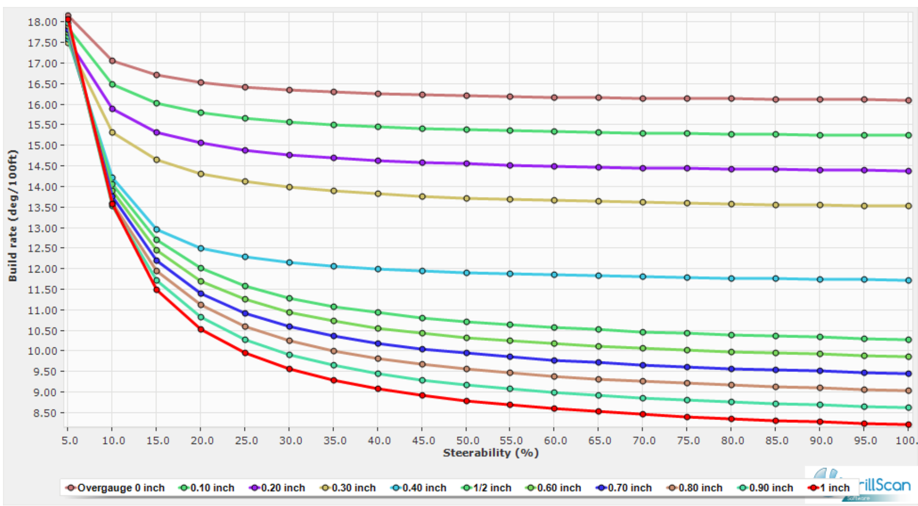


Figure 5: Build rate as a function of bit steerability and hole over gage – Sliding mode – TFO =0 deg – Inc. = 45deg

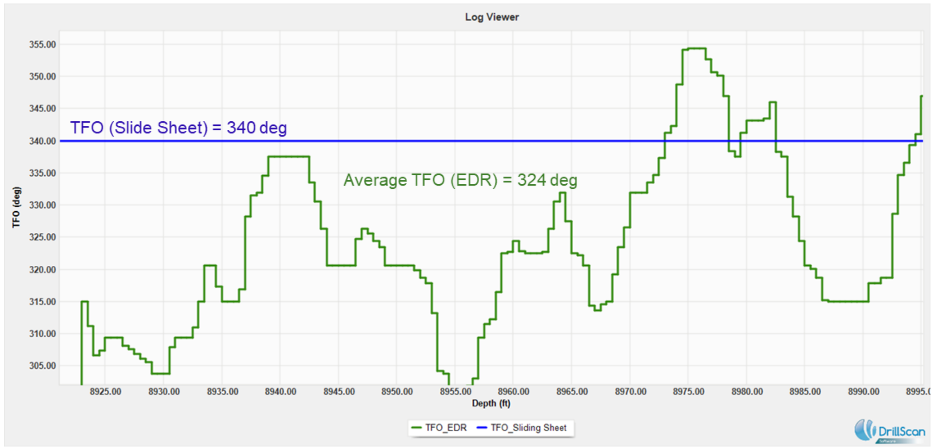


Figure 6: Tool Face Orientation: Slide sheet versus EDR

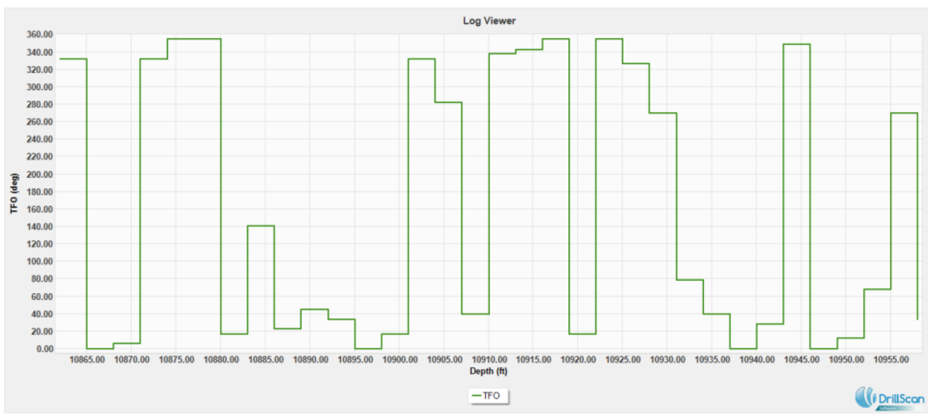


Figure 7: Erratic Tool Face Orientation – EDR data – TFO target = 0 deg.

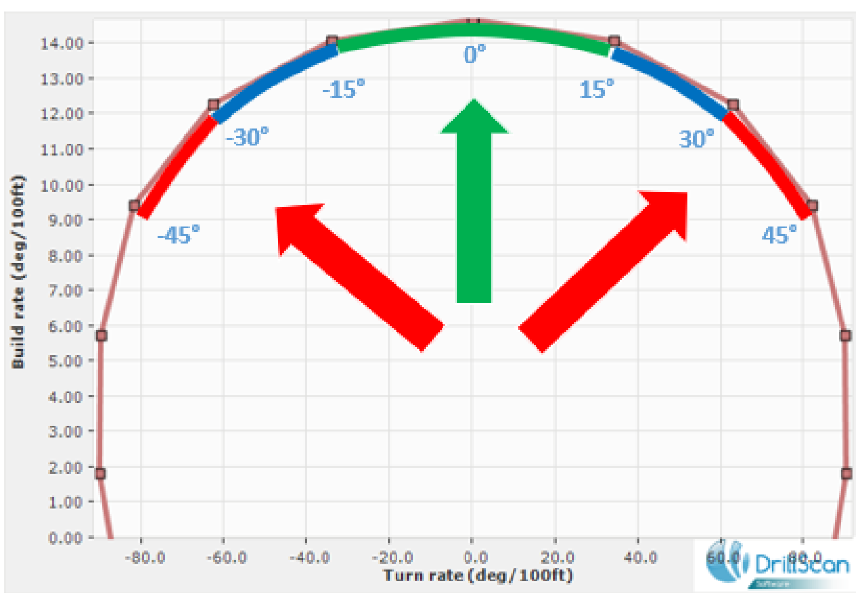
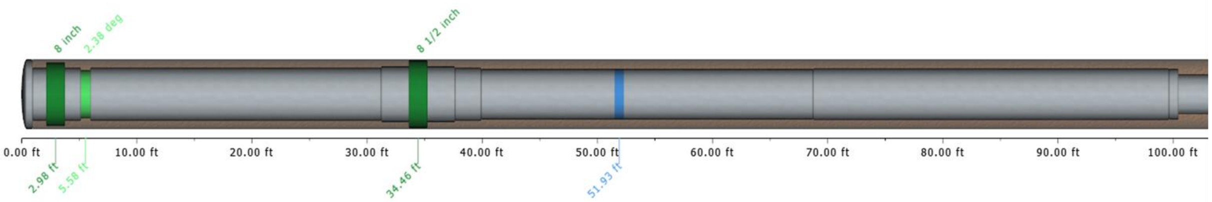


Figure 8: Calculated Build/Turn Rates for different TFO values – Sliding mode. OVG = 0in.

Table 1: 8 ¾" BHA characteristics

Type	Name	Length (ft)	OD (inch)	ID (inch)	Gauge (inch)	Total length (ft)	Contact (ft)	Mass (lb)	Total mass (lb)	Linear mass (lb/ft)	OD tooljoint (inch)
PDC	PDC bit	0.98	-	-	8 3/4	0.98	-	99.05	99.05	100.64	-
Steerable mud motor	6 3/4" Motor 7/8, 5.7, - 2.38	30.27	6 11/16	2 13/16	-	31.25	-	2978.41	3077.46	98.39	-
STA	-	-	-	-	8	-	2.98	-	-	-	-
BNT	-	-	-	-	-	-	5.58	-	-	-	-
Other	8 1/2 NM Stabilizer	6.42	7	2 3/4	8 1/2	37.67	34.46	711.06	3788.52	110.76	-
Other x 1	Mule Shoe	2.26	6 11/16	2 9/16	-	39.93	-	230.49	4019.01	101.99	-
MWD	NMDC	28.83	6 3/8	2 7/8	-	68.76	-	2494.77	6513.78	86.53	-
Sensor package		-	-	-	-	-	51.93	-	-	-	-
Flex x 1	NM Flex Collar	30.91	6 1/2	2 7/8	-	99.67	-	2807.72	9321.50	90.84	-
DP x 345		10874.40	5	4 1/4	-	10974.07	-	231346.22	240667.72	21.27	6 3/8
HWDP x 30		909.30	5	3	-	11883.37	-	41054.68	281722.40	45.15	6 1/2
DP x 1		31.52	5	4 1/4	-	11914.89	-	670.57	282392.97	21.27	6 3/8



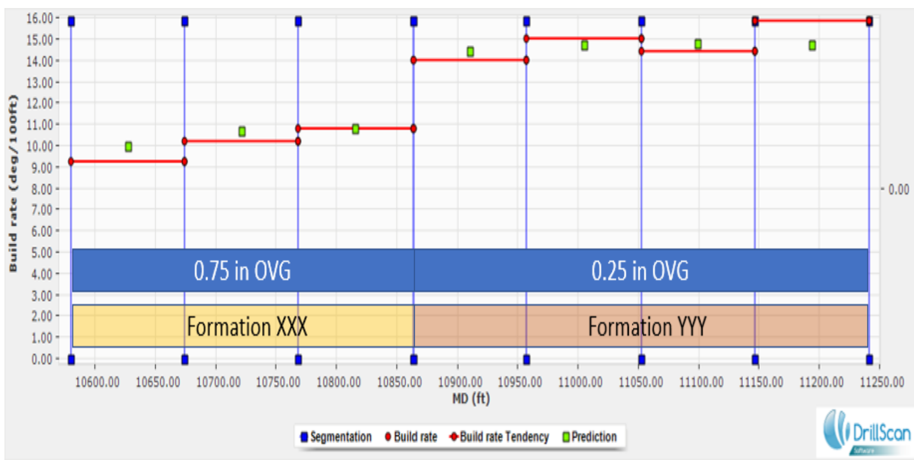


Figure 9: Predicted versus Actual build rate in 2 different formations - Curve

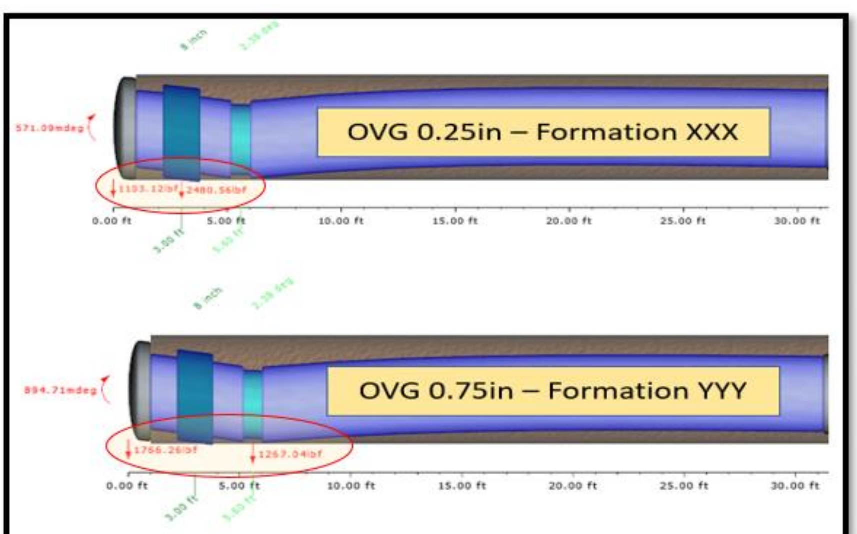


Figure 10: Difference in contact points with 0.25in. vs 0.75in. hole overgauge

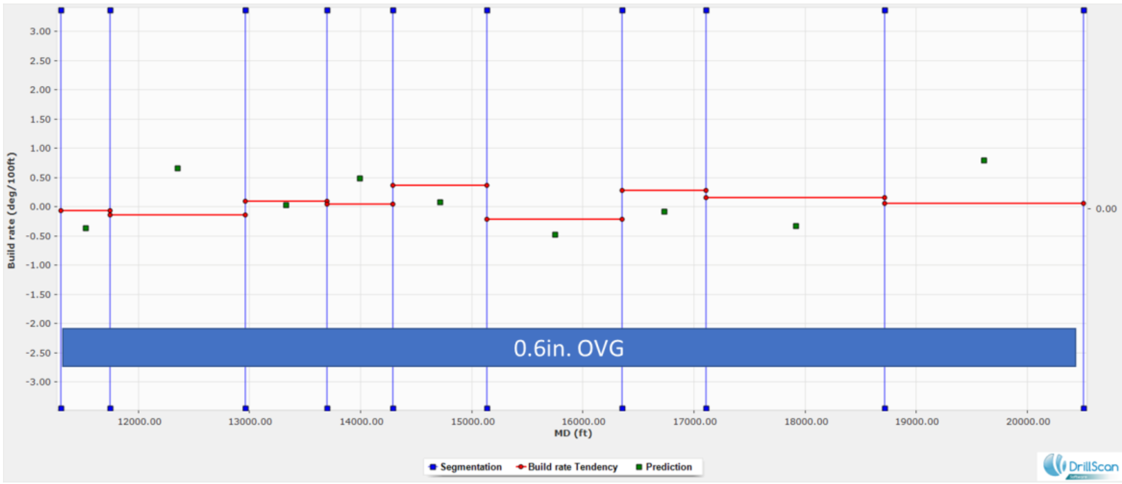


Figure 11: Post Analysis Build Rates Across Lateral Section

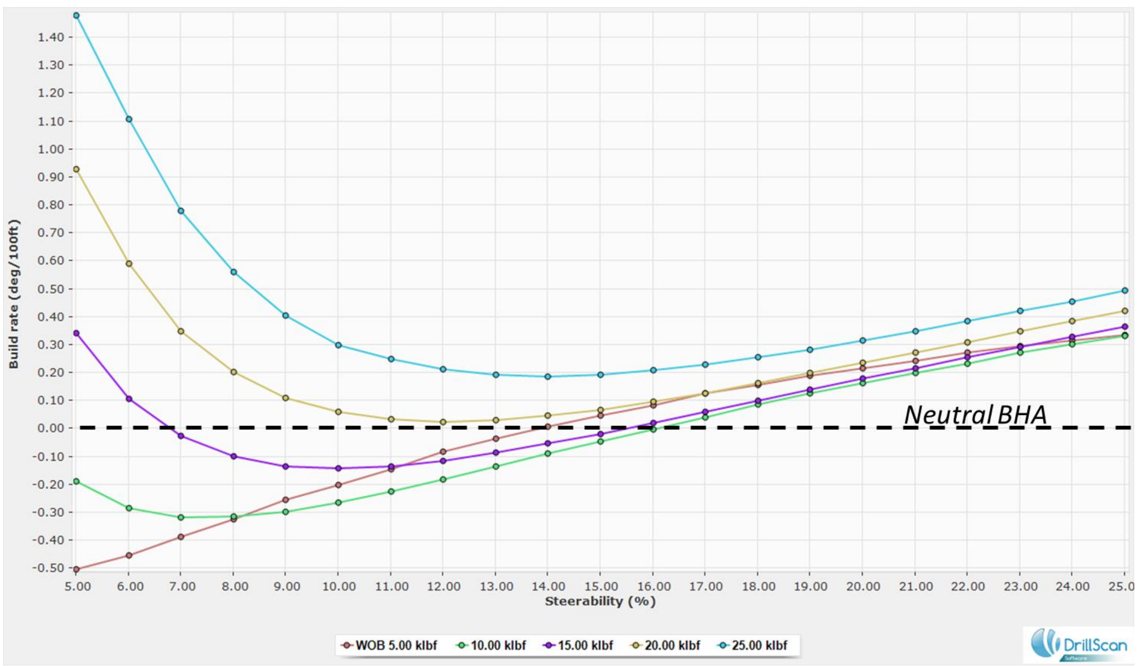


Figure 12: BHA Rotating Tendency – Inc.= 90deg. – Effect of WOB & Bit Steerability – OVG = 0.6in.