AADE-03-NTCE-24

A Graphical Hole Monitoring Technique to Improve Drilling in High-Angle and Inclined Deepwater Wells in Real-Time

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Abstract

Monitoring cuttings transport and hole integrity in highly deviated wellbores is challenging. Typical problems associated with these well designs are torque and drag limitations, wellbore stability, mud rheology and solids control, and directional well design. A graphical presentation of simple drilling hook loads and torques versus theoretical calculations vastly improves real-time adjustments to drilling practices as hole conditions change and provides early warning of poor hole cleaning and wellbore stress failures in inclined wellbores. Poor drilling techniques are easily identified from reported hook load measurements and can be corrected quickly. While only simple hook load and torque measurements are required to detect hole problems, integration of annular pressure-while-drilling (APWD) and logging-while-drilling measurements is shown to improve the interpretation of root causes of hole problems in several examples of deepwater and high-angle wells. Small changes in surface measurements can quickly highlight deteriorating hole conditions in these wells. The graphical presentation improves communication of hole issues in an effective manner to both rig and office personnel in an easily understood format.

While running casing normally takes only a small percentage of the well development life cycle, the consequences of failing to get the casing to section total depth are very significant in terms of additional cost and time. It is difficult to predict well friction factors using only theoretical understanding and modeling; extensive experience in these matters is required to perform effectively. The graphical technique, used while drilling, allows the accurate determination of friction factors that can be used to ascertain casing running loads while also providing a quick method to monitor these actual loads and points of no return.

Introduction

The main challenges of most deviated wellbores are hole cleaning, wellbore stability and torque and drag issues. These issues are actually concerned with borehole quality and require more emphasis then for vertical wellbores, particularly in high-cost drilling environments such as deepwater or remote locations. The advent of torque and drag modeling has improved the planning of these wells, but requires "experts" to calibrate models, produce accurate interpretations and to determine the proper course of action. The problem for drilling personnel is that these "experts" are seldom at the rigsite where the real-time decisions are needed to prevent non-productive time events.

This paper discusses a graphical method of monitoring hole conditions in real-time, at the rigsite, using simple surface measurements recorded by the driller. This technique still requires modeling of torque and drag for each hole section, but can be performed in the town and sent to the rig for real-time monitoring. The graphical output provides:

- A simple visual method of checking the accuracy of the torque and drag model,
- Allows easy calibration of the torque and drag model visually,
- Provides real-time detection of poor drilling trends related to hole cleaning, wellbore stability and micro-dogleg problems
- A simple method to communicate these trends to rig personnel and town, and
- A qualitative check of the driller's ability to monitor hole conditions using rigfloor gauges.

Experience has shown that measured hookload deviations from theoretical hookloads, provide a very robust method of monitoring hole conditions. Further enhancement is obtained with LWD tool measurements to improve "root cause" determination at the rigsite. While an in-depth understanding of torque and drag modeling is not required to use these "plots", a basic understanding will improve the ability to make interpretations quickly.

Torque and Drag Theory

Torque and drag issues are particularly prominent in deviated and horizontal wells, due to the effects of the weight of the drillstring on the lower side of wellbore. Excessive drag can prevent directional control with steerable motor systems, create problems when tripping, cause stuck pipe, drillstring buckling and exceed rig capabilities. Excessive torque can damage rig equipment, create shocks that damage drillstring components and exceed the capacities of the drillstring.

Torque and drag modeling is performed using finite element models which divide the drillstring into individual elements. Sideforces are then calculated for each element. The sliding friction force F is calculated as follows:

$$F = \mu * N$$

where N is normal contact force between drillstring and wellbore, and μ is the coefficient of friction, or 'friction factor' used to represent the average conditions in the wellbore. The rotating friction, or torque, is determined for each element as follows:

$$F = \mu * N * r$$

where r is the radius of the drillstring element. Sum of the sliding forces for the entire drillstring is the hookload weight and the sum of the rotating forces is the torque required to turn the drillstring. Since the modeling of torque and drag requires a sideforce, these models are for deviated wells only as no sideforce exists in vertical wells.

Stated simply, drag is the resistance force that must be overcome to move the drillstring up or down in the wellbore. While torque is the moment force required to rotate the drillstring. Both are related to the sideforces and friction generated in the wellbore. Sideforces are the normal, or perpendicular, forces exerted on each element of the drillstring due to:

- Buoyant weight of each drillstring component,
- Tensile load across element (total is often referred to as hookload),
- Buckling and bending loads across each drillstring element, and
- Drillstring component stiffness across hole curvature and micro-doglegs.

The two major contributors to torque and drag are the weight of the drillstring and the tensile load across each element of the drillstring. From Figure 1, it can be clearly seen that as the inclination of the wellbore increases, so does the normal force for each drillstring element. Likewise, in figure 2, the normal force due to tensile load increases with both the weight of the drillstring below each element and as the wellbore curvature, or dogleg, increases. It is also obvious that the wellbore sections in which the inclination is dropping, results in much higher tensile sideforces then in a build or tangent section as the tensile and weight force vectors are in the same direction.

Wellbore friction is generally represented as a coefficient of friction, "friction factor", and is the force opposing motion of the drillstring. Wellbore friction is a function of the materials interacting and the lubricity of the mud in the wellbore. The materials interacting in the wellbore are typically metal drillstring components and the metal casing and/or formations.

Drilling Problems

During drilling, the surface measurements of torque and hookloads are invaluable indicators of hole conditions. By plotting the pick-up, slack-off, rotating weights as well as drilling torque, trends can be identified. The key to detecting these trends quickly is to plot the actual data versus theoretical values for each hole section. This technique identifies abnormal trend changes from normal drilling loads as well depth and trajectory changes.

Increases in torque and drag can be a warning sign of problems such as:

- the build-up of a cuttings beds on low-side of the wellbore
- wellbore stability issues such as wellbore break-outs and hole enlargements
- tight hole conditions; ie, reactive shales, key seats, differential sticking,
- tortuosity in wellbore, especially micro-tortuosity and wellbore spiraling, and
- rig equipment problems; ie, topdrive bearing failures, high riser bending, torque gauge calibrations, etc.

For wellbores in good condition, the primary source of drag is sliding friction due to contact between the drillstring and the wellbore. Other surface measurements such as flow rate and circulation times can be added to the plot to aid interpretation.

Advanced Interpretation of Drilling Problems

The combination of advanced MWD/LWD measurements with hookload charts and a rigsite drilling mechanics expert will vastly reduce mechanical drilling risks. MWD/LWD measurements such as annular pressure and gamma ray can be added to the plots to improve interpretation. While adding such measures improves interpretation of drilling problems, these measurements require broader skills by the user. Specially trained drilling mechanics engineers are becoming increasingly utilized in high-cost and high-risk rigsites. PERFORM, Performance Thorough Risk Management, engineers are especially trained in drilling mechanics and wellbore stability issues. These engineers concentrate solely on drilling mechanics, wellbore stability and pore pressure issues while drilling and risk assessment from offset well data.

Accurate Drilling Data

As with any analysis, "junk data in equals junk data out". While the surface measurements of hookloads and torque are simple measurements, these measurements are not so easily obtained on the rig. The importance of accurate measurements is essential to monitoring trends. Figure 3 is an example of poor drilling data collection. The actual hookloads are the solid curves and the "stair-step" and "blocky" patterns are indicators of poor data but also of the bigger issue of driller training and drilling practices. Even with the theoretical modeling properly calibrated, there is little value in plotting the poor quality data on the graph. One of the primary obstacles for drilling mechanics experts, at the rig, are the training of drill crews in proper drilling techniques including:

- proper speed control when raising and lowering the drillstring,
- maintaining consistent drilling practices between drill crews,
- understanding swab/surge effects,
- tripping practices,
- proper hole cleaning practices, and
- recognizing the symptoms of downhole shocks and vibrations.

Figure 4 is a plot of surface hookloads obtained properly using consistent drilling practices. Note how the actual hookloads overlap the theoretical curves and increase gradually with depth.

Hookload Charts and Friction Factor Calibration

The rotating off-bottom, pick-up and slack-off hookloads are used to calibrate the torque and drag model. Hookload points are taken after drilling out the casing shoe at every connection. These hookload and torque points are taken as follows:

- accurate block weight must be known,
- all measurements taken while circulating at drilling flow rates,
- rotating off-bottom hookload is taken at drilling rotary speed and close to bottom with minimum rpm of 30,
- pick-up and slack-off weights are measured at constant block speed, which should be slow and continuous,
- measurements read from driller's weight indicator to nearest 2 klbs,
- torque measured off-bottom at drilling rotary speeds while circulating at the drilling flowrate with the traveling block stationary; this removes the variable bit torque from measurement.

If the rotating hookloads follow the theoretical rotating hookloads, then the traveling block, BHA and drillstring weights are correct. The correlation should be exact with same slope and accurate block weight must be included in the theoretical model. Rotating off-bottom negates friction for the hookload measurement and represents the buoyant weight of the drillstring. Secondly, in the first few connections out of the casing shoe, the hole is relatively clean of cuttings, in gauge, and is the best time to determine "clean hole" friction factors for the well. Once the rotating weight is correct, the friction factors used in the theoretical model are adjusted until the pick-up and slack-off hookloads match the theoretical curves. This friction factor is the "clean hole" value with the current mud weight and mud properties. Once the theoretical and actual hookloads are in agreement at the beginning of the hole section, the modeled hookloads are only modified if there is a major change in mud weight or lubricity of the mud system in that hole section. This simplifies the modeling procedures and allows monitoring of trends easily.

The importance of the theoretical hookload values can be seen in Figures 5 and 6. Figure 5 is a hookloads chart without the theoretical (modeled) curves. This is a 62-degree well where the 12 ¼" hole section is the tangent section. The rig capacity is the limiting factor for hole cleaning while drilling this section. The drilling techniques are good for the first part of the hole section, but are not adapted as the increasing pump pressure, with the small drillpipe, reduces flow rates. It is difficult to determine if the hole conditions are deteriorating and the interpretation is difficult. There are hole-cleaning problems, but what depth did the problems begin? Adding the theoretical hookloads in figure 6, simplifies the interpretation and the hole cleaning problems are seen to begin at a depth of 14,700 feet and are becoming worse. Corrective actions can be taken quickly before the situation results in additional non-productive time.

Figure 6a is a torque chart that is similar to the hookload charts. The theoretical torque curve is on the chart and actual off-bottom torque values are plotted for comparison. Similar to the modeled hookload calculations, the drillstring sideforces are used for the theoretical torque calculations as well. Unlike the hookload calculations, the torque modeling is complicated due to the effects of drillstring rotation speed. As the drillstring rotation speed changes, the sideforces change along the drillstring due to centrifugal forces that are not possible to model accurately. Theoretical torque values are best used to detect downhole vibrations that waste drilling energy and show up on the rig floor as increased torque and/or erratic torque values. Off-bottom torque values are the preferred values to use as the bit torque is removed from the simulations. The bit torque is difficult to model as the bit torque varies with formation strength, weight on bit, bit speed and bit design.

Poor Hole Cleaning Example

An extended reach well, with hole cleaning problems, is shown in Figure 7 using oil-based mud. LWD gamma ray curves were added to the hookload chart to assist the interpretation of hole cleaning and wellbore stability problems. The increasing pickup hookloads are indicating problems in the well below 14,500 ft. The gamma ray curve is used by the PERForm engineers at the rigsite to monitor sand formations drilled and their affect on hole cleaning. The MWD annular pressure while drilling (APWD) sensor also indicated hole cleaning problems but not until below 15,000 ft. Because the equivalent circulating density (ECD) calculation is a function of true vertical depth (TVD), in high angle wells, the ECD measurement does not respond as quickly to cuttings buildup on the low-side of the wellbore as does the pick-up hookload measurements. This phenomenon has been seen in many high-angle wells and is one of the primary reasons for the increasing use of hookload charts to improve the detection of hole cleaning problems in high angle wells. In this well, hole cleaning could not be improved while continuing to drill. Controlling the penetration rates after the problems occurred did not improve pick-up hookloads or ECD issues. Corrective action required stopping drilling and circulating while rotating the drillstring until the cuttings beds were removed. Once the cuttings beds were removed, drilling continued with controlled penetration rates and optimizing circulating times between connections to prevent further problems.

Another hole cleaning problem is illustrated in Figure 8. Hole cleaning problems begin below 11,000 feet in a 67-degree well. Problems increase rapidly to 12,500 feet where a trip is made to clean the hole mechanically. Circulation times between connections are added to the plot to optimize circulation times between connections. Multiple friction factor hookload curves were added to the plot as relative measure of deteriorating hole conditions. Hole cleaning was related to penetration rates in this well as flow rate was limited due to surface pump pressure limitations. Penetration rates exceeding 100 fph resulted in cuttings beds on the low-side of the hole. Back-reaming at connections did not improve hole cleaning or removal of cuttings beds. The friction factors for the hole had increased from the 0.17 value for a clean hole to more then 0.22 or a 30% deterioration of hole quality. Recommendations to discontinue drilling and circulate the hole clean with high drillstring rotation were not accepted by the client. As a result, when total depth was reached, the rig spent the next 2 ½ days trying to pull out of the hole and became stuck and packed-off in the hole several times.

The effects of drilling different formations on hole cleaning is illustrated in Figure 9. This is a deep well to 22,000 feet using water based mud and a rotary steerable tool to improve hole cleaning by allowing continuous drillstring rotation while drilling. Circulation times between connections are plotted on the right side of the hookload chart and multiple theoretical hookloads are plotted for two different friction factors. In the previous hole section, the “clean hole” friction factor was 0.20. After drilling out the cement and shoe track of the 9 5/8” casing, the pickup hookloads are indicating poor hole cleaning as the cement cuttings were not sufficiently circulated out of the 73-degree well due to poor mud quality. At 17,800 feet, a trip was made due to a downhole tool failure, the mud was conditioned and cuttings bed was removed.

As drilling resumes following the trip, hole cleaning is continuously improved while drilling shale formations and the circulation times are reduced to find the optimized hole cleaning time. This trend is reversed as fine sand formations are drilled below 19,000 feet as seen on the gamma ray curves and pick-up hookloads. Two stands were racked back at 19,200 feet and the hole circulated to assist removal of the cuttings beds on the low-side of the hole. As more sand is drilled, hole cleaning is not improved and a short trip is made at 20,500 feet to mechanically clean the low side of the hole and check hole conditions. The pink curve is the TOOH hookloads during the short trip overlaid on the hookload chart. Increasing tripping hookloads indicated wellbore stability problems causing additional hole cleaning problems. Hole cavings, as shown in Figure 10, were seen on the shale shakers by the PERForm engineers that confirmed wellbore breakouts and that additional mud weight was needed to control wellbore stability.

Tripping Hookload Example

Figure 11 is series of two BHA trips in a 17 ½" section of a directional well. Theoretical tripping hookloads are plotted as dashed lines for friction factors of 0.20 and 0.30. For water-based muds, tripping friction factors below 0.30 are considered a relatively clean hole in good condition. The first TOOH occurred at 4600 ft and experienced high drag between 3900-4200 feet. The TIH experienced similar drag going back in the hole. At 4050 ft, the hole was conditioned and large amounts of cuttings were seen at surface. The drag was reduced on the next stand in the hole, but returned on the following stands until below 4200 ft. These high drag sections correlated with a sand section with laminated shale stringers which washed-out leaving ledges in the hole. The last trip out of hole, at casing point deoth, had much improved drag over previous trips as seen on the purple hookloads curve.

Casing Running Hookload Examples

Hookload modeling charts can be produced to monitor casing running operations as well as drilling operations. Figure 12 is a hookload chart for the running of a 13 3/8" casing string in a 38-degree well. The actual hookloads track a constant friction factor profile indicating good hole conditions through the buildup curve to total depth. Figure 13 is the hookload chart for running the 9 5/8" casing string. Multiple theoretical hookloads corresponding to various friction factors are shown by the colored bands. Increasing drag, and increasing friction factors, are to the left-side of the chart. As the 9 5/8" casing enters open hole at 7600 feet, the hookloads are indicating negative friction factor values, which is due to casing beginning to "float" until fill-up is achieved. Below 9000 feet, the casing begins hanging on ledges as seen on the gamma ray curve. Measured friction factors increase three hundred percent to 0.65. Once circulation is established below 11,000 feet to clean up the low side of the hole, the drag is reduced and the hookloads are reduced less then a 0.20 friction factor. Washing of the casing continued, but below 13,000 feet the hookloads remained constant. As the theoretical curves indicate, the casing weight should be increasing as depth increases. In effect, drag is increasing even though the casing hookloads are relatively constant values. The casing had already exceeded the point of no return. This is the depth in which, once exceeded, the casing could not be pulled out of the hole due to either rig or casing strength limitations and the rig was committed to continuing to wash the casing in the hole. The casing string became stuck off-bottom at 15,100 feet and was cemented in place. The use of hookload charts for running casing strings can be used to determine the depth of no return and to plan contingency operations before reaching that depth.

Evaluating Mud Additives Example

In figure 14, the torque chart illustrates the effects of mud lubricants on surface torque and downhole drilling mechanics. High stick-slip can be seen in the build-up and beginning of the tangent sections to 8000 ft. Mud lubricants were added to the water-based mud at 8,000 feet to reduce erratic torque values. Immediate results are seen on both torque and stick-slip values. While the stick-slip vibrations remain greatly reduced over the 12 ¼" hole section, drilling torque values increase within the next 1000 ft. Evaluation of the mud lubricants based solely on surface torque readings would suggest very limited success, but based on the reduction in severe stick-slip conditions, the mud lubricants prevented drillstring failures. To improve the effects on surface torque, mud lubrication concentrations should be increased and further improvements in hole cleaning were recommended. Erratic surface torque values are actually indicating that more then lubricity improvements are required to reduce the surface torque. Hole cleaning issues in the 56-degree tangent section are contributing to the torque problems. Typically, hole inclinations from 40-60 degrees are the most difficult to clean due to cuttings beds sliding downhole when flow rates are reduced. Annular pressure sensors can be used to improve interpretation and evaluation of hole cleaning techniques.

Conclusions

1. A graphical presentation of simple drilling hook loads and torques versus theoretical calculations vastly improves real-time adjustments to drilling practices as hole conditions change and provides early warning of poor hole cleaning and wellbore stress failures in inclined wellbores.

2. Integration of annular pressure-while-drilling (APWD) and logging-while-drilling measurements improve the interpretation of root causes of hole problems high-angle wells.

3. The graphical presentation of hookload and torque data improves communication of hole issues in an effective manner to both rig and office personnel in an easily understood format.

4. The graphical technique, used while drilling, allows the accurate determination of friction factors that can be used to ascertain casing running loads while also providing a quick method to monitor these actual loads and points of no return.

5. The graphical output provides a simple visual method of checking the accuracy of the torque and drag model and a qualitative check of the driller's ability to monitor hole conditions using rigfloor gauges.

6. The graphical torque charts can be used to evaluate the effects of lubricants to the mud system.

Nomenclature

APWD = *annular pressure while drilling measurement*
BHA = *bottom-hole assembly*
ECD = *equivalent circulation density*
EMW = *equivalent mud weight*
FPH = *feet per hour*
LWD = *logging while drilling tools*
MWD = *measurements while drilling tools*
N = *normal force (sideforce)*
ROP = *drilling rate of penetration*
rpm = *revolutions per minute*
TOOH = *trip out of hole*
WOB = *weight on bit*

Acknowledgments
The author would like to thank the many field engineers and Drilling Engineers that provided data to make this paper possible.

Author
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Figure 1- Sideforce for the weight component of a drillstring element

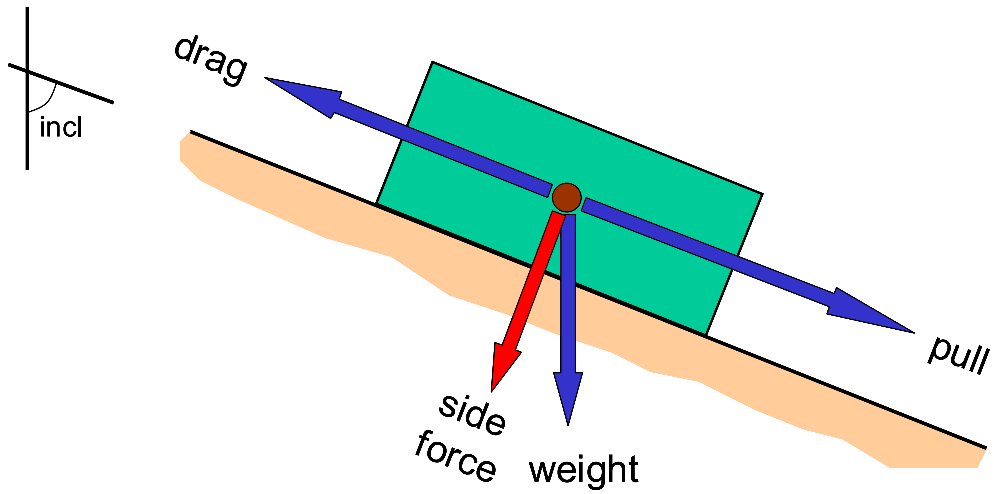

Figure 2- Sideforce for the tensile component of a drillstring element

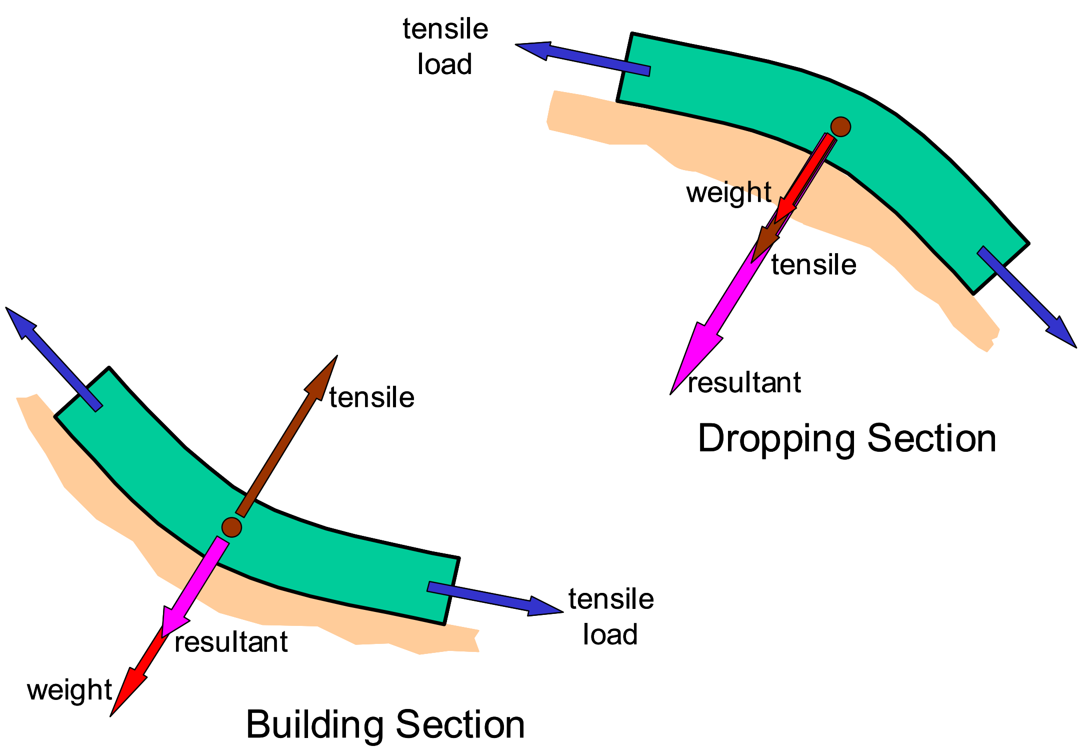

Figure 3- Hookloads Chart - poor surface data measurements example

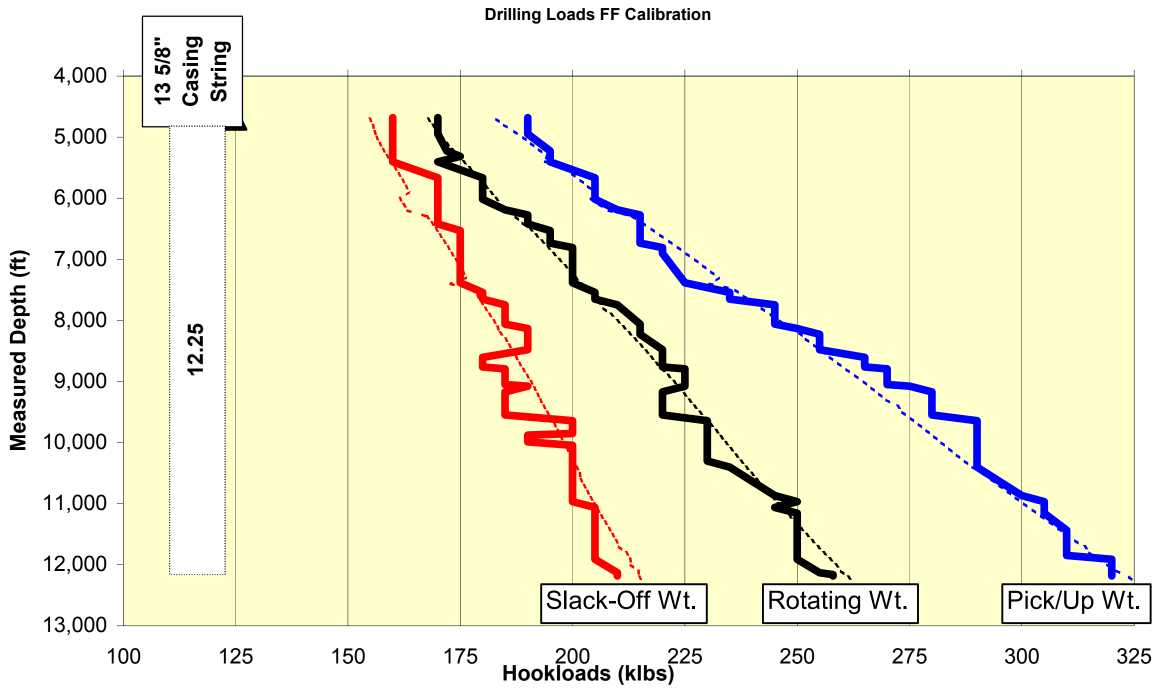

Figure 4- Hookloads Chart - good surface data measurements example

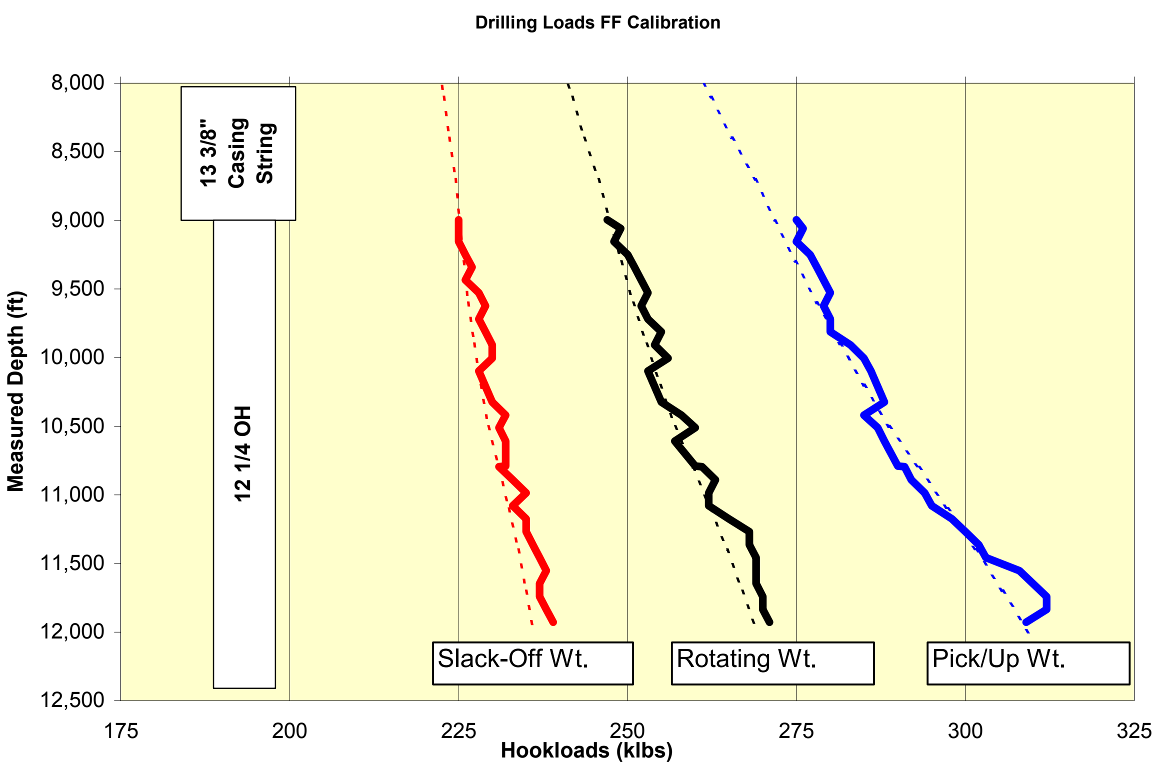

Figure 5- Hookloads Chart - hole cleaning example without theoretical hookloads

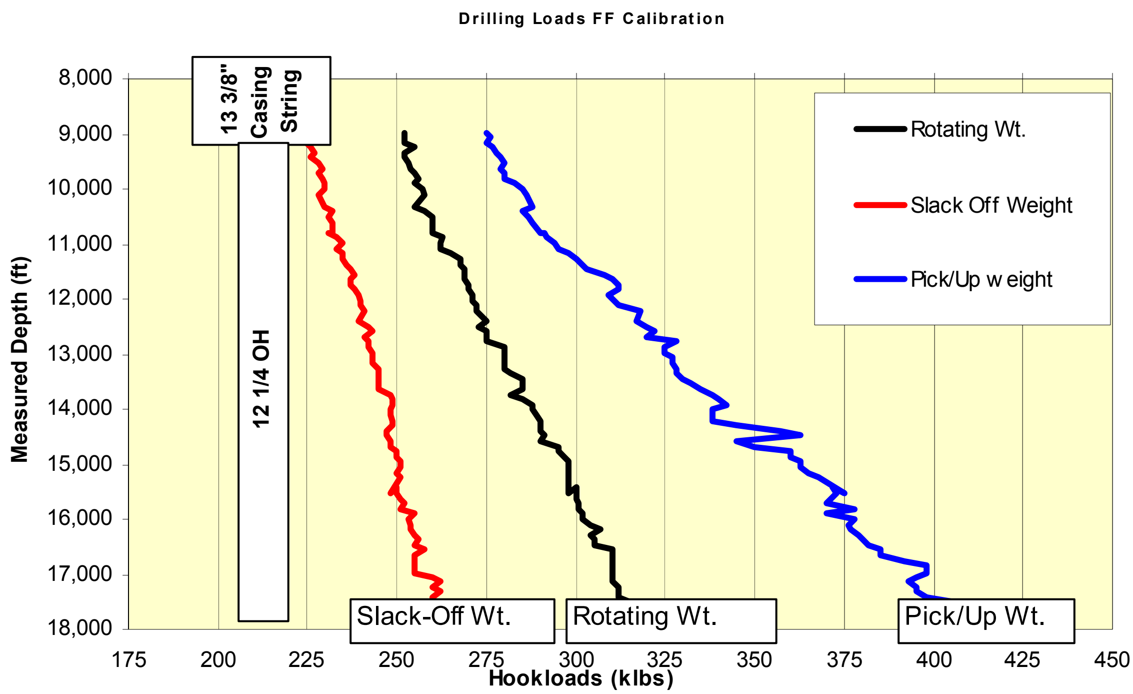

Figure 6- Hookloads Chart - hole cleaning example with theoretical hookloads

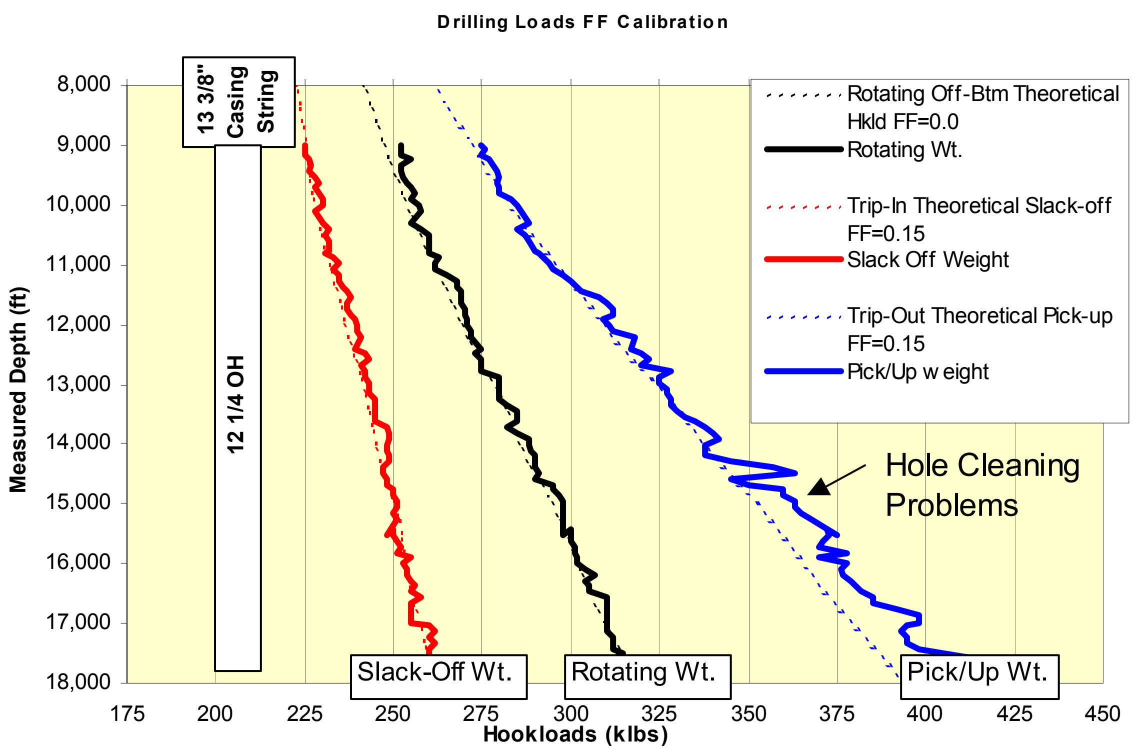

Figure 6a- Torque Chart – off-bottom and theoretical torque curves

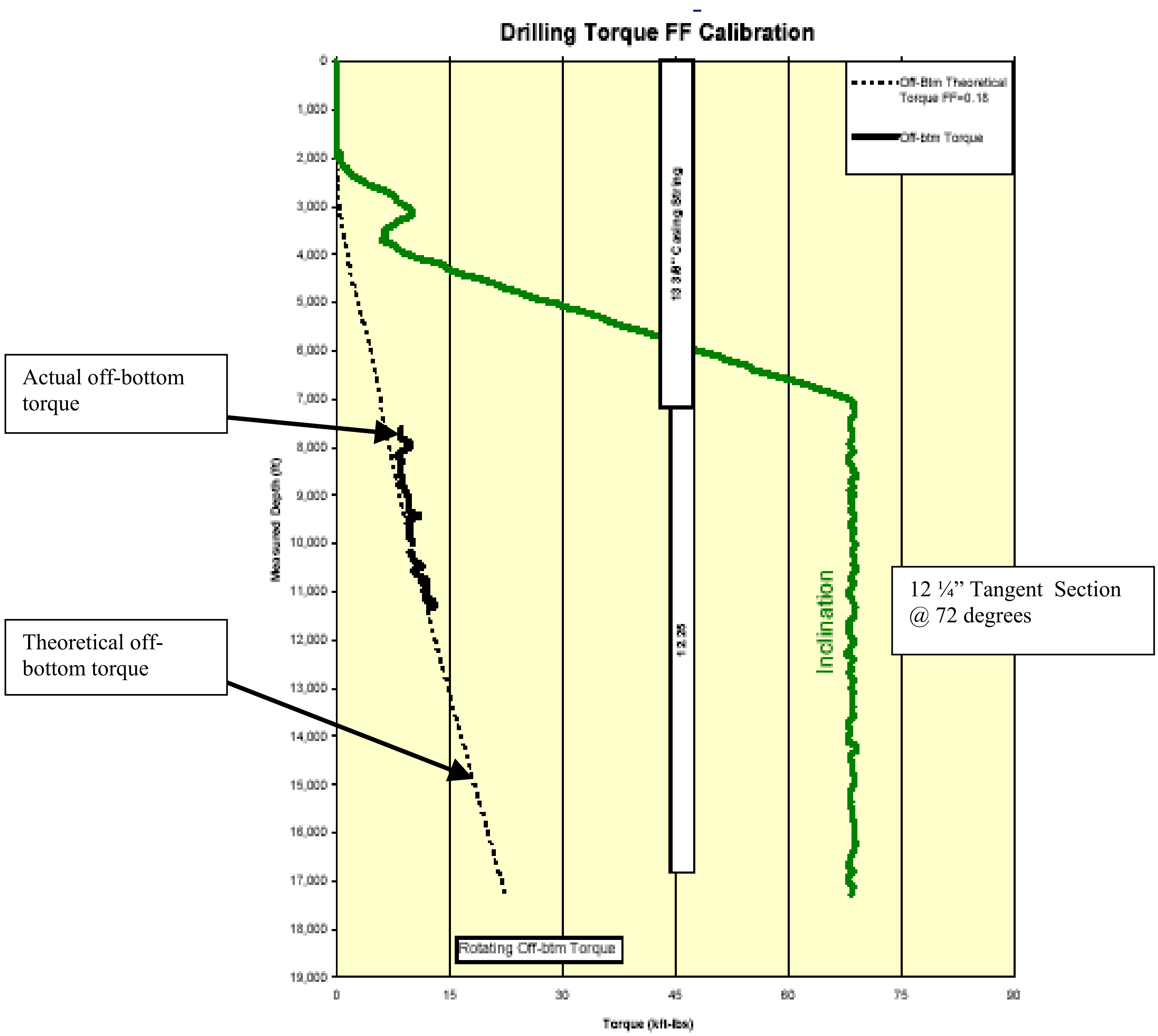

Figure 7- ERD poor hole cleaning example in 12 ¼" hole size

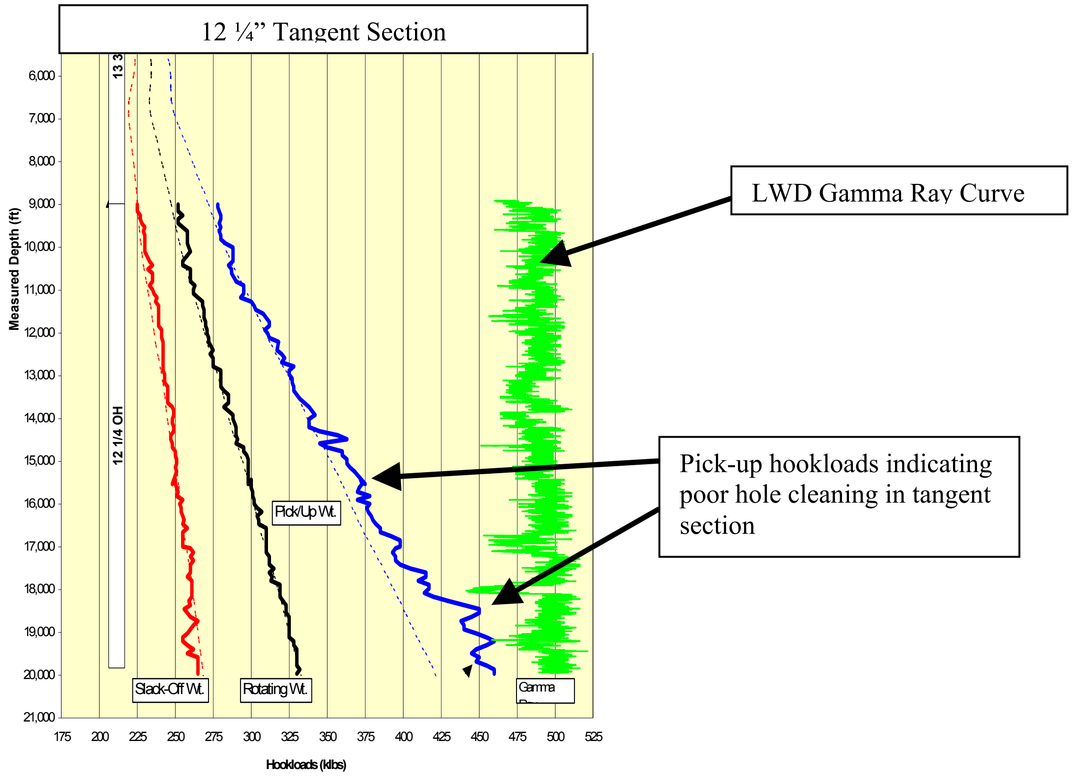

Figure 8- Poor hole cleaning example in 12 ¼" hole size

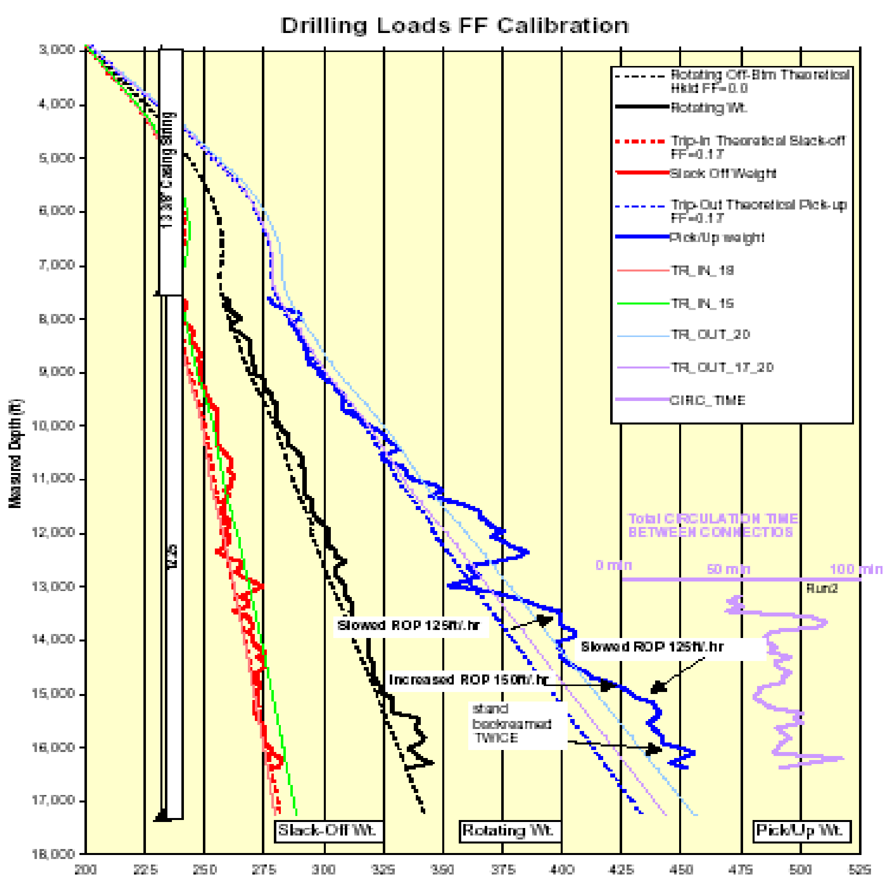

Figure 9- ERD poor hole cleaning example in 8 ½" hole size

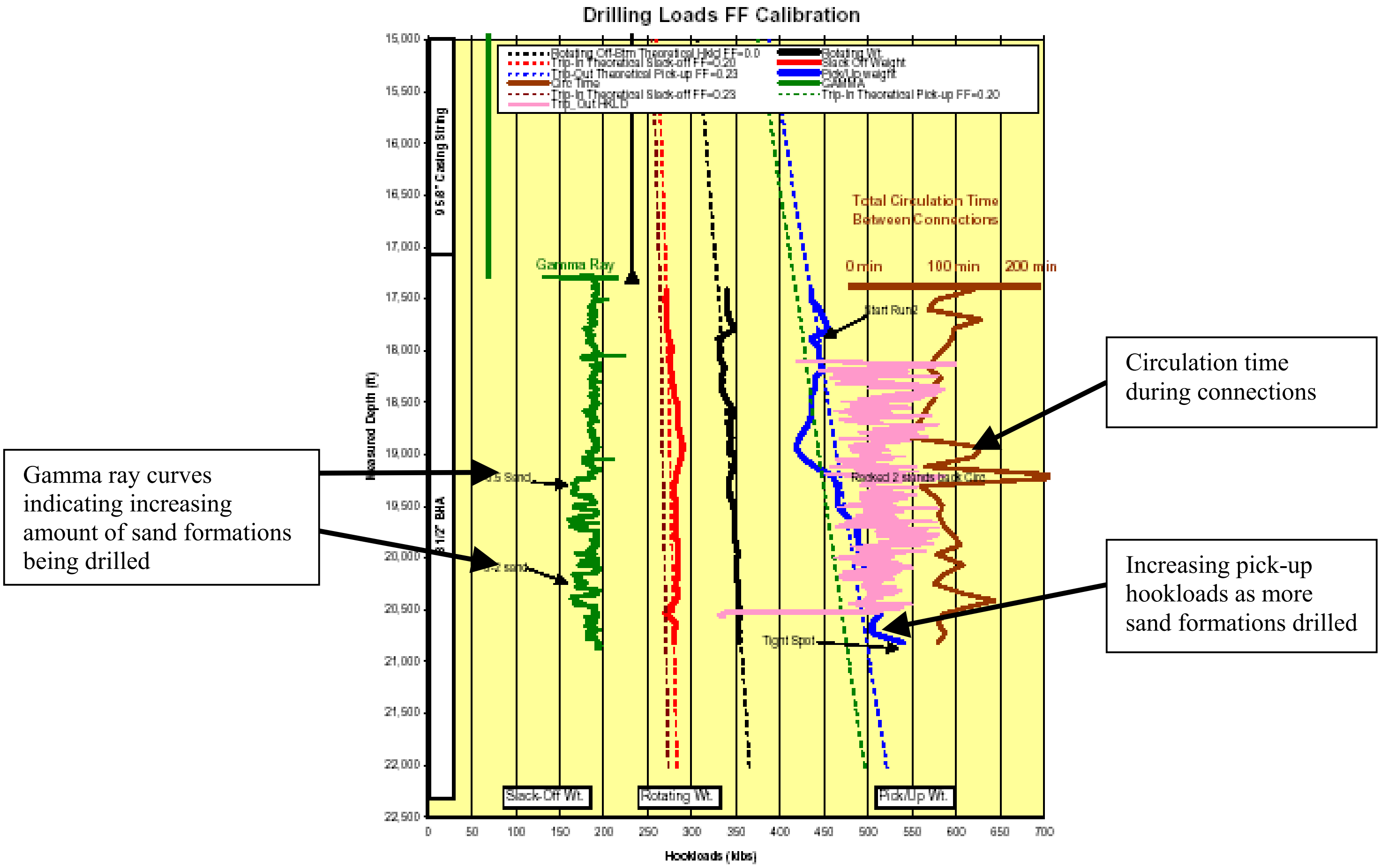

Figure 10- Hole cavings from high angle well

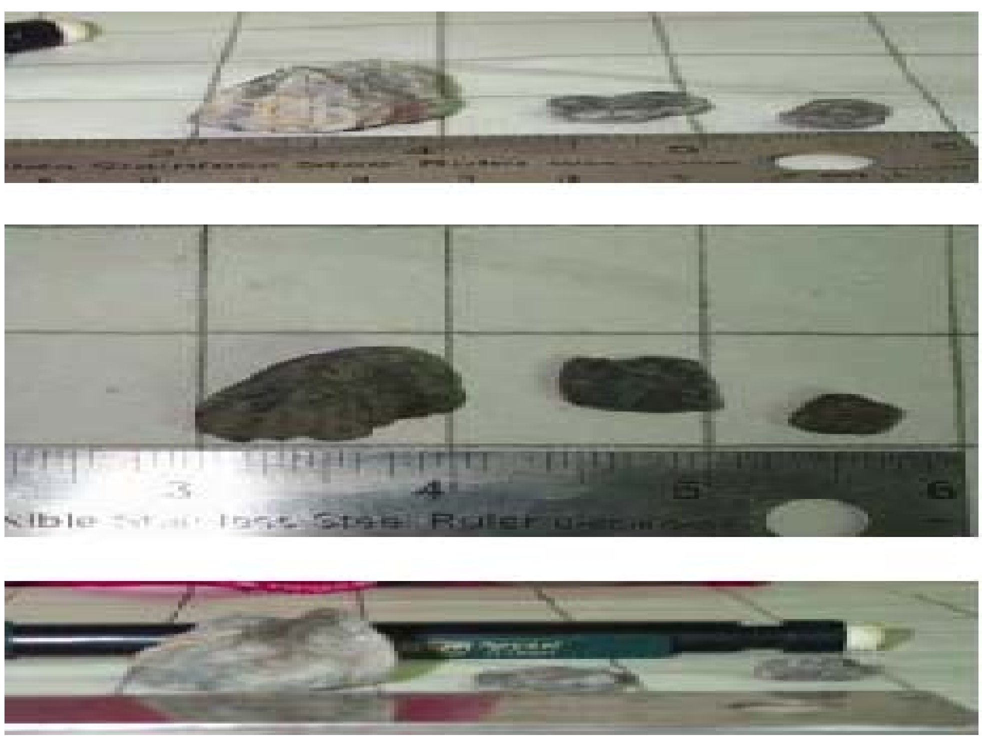

Figure 11- Tripping Hookloads Chart

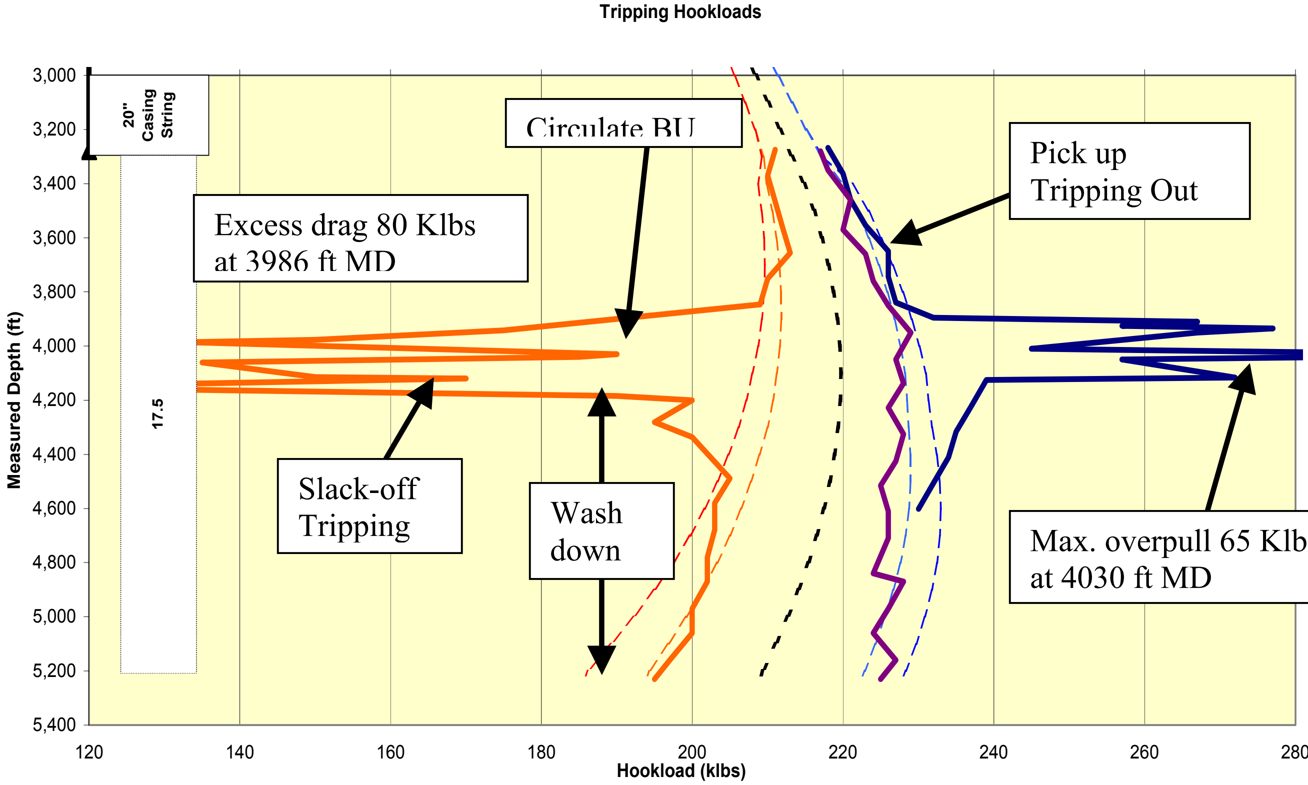

Figure 12- Casing Running Chart – good hole conditions

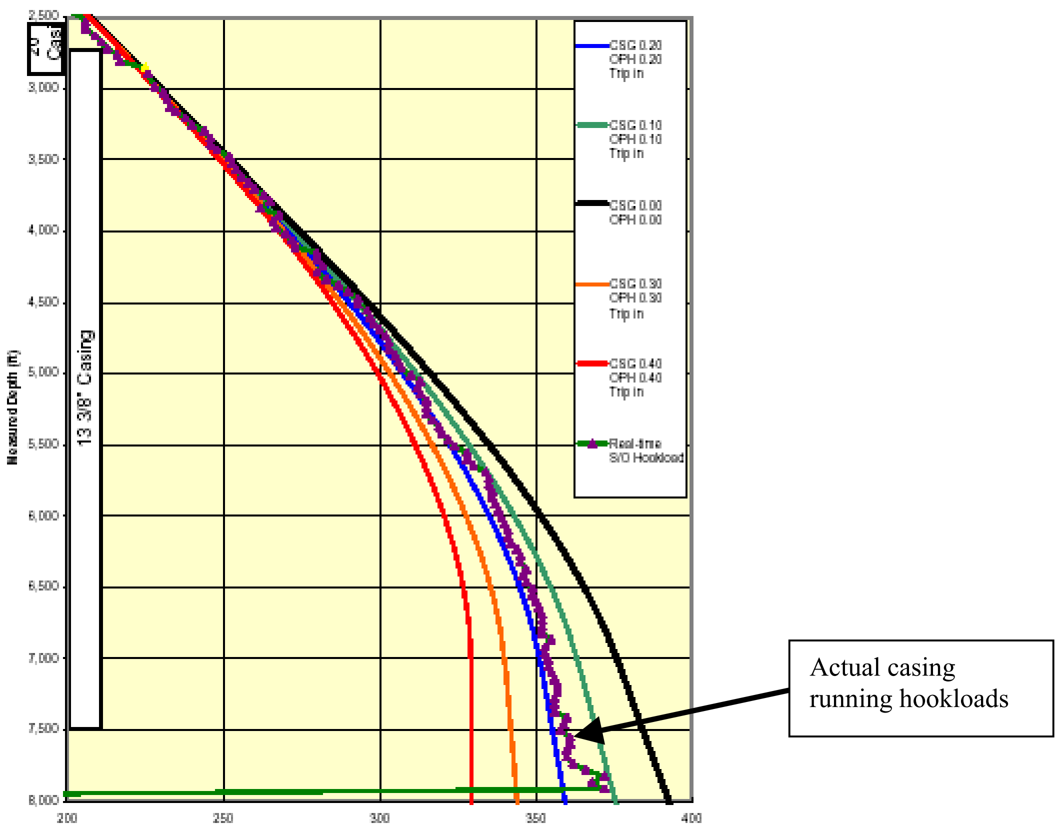

Figure 13- Casing Running Chart – poor hole conditions

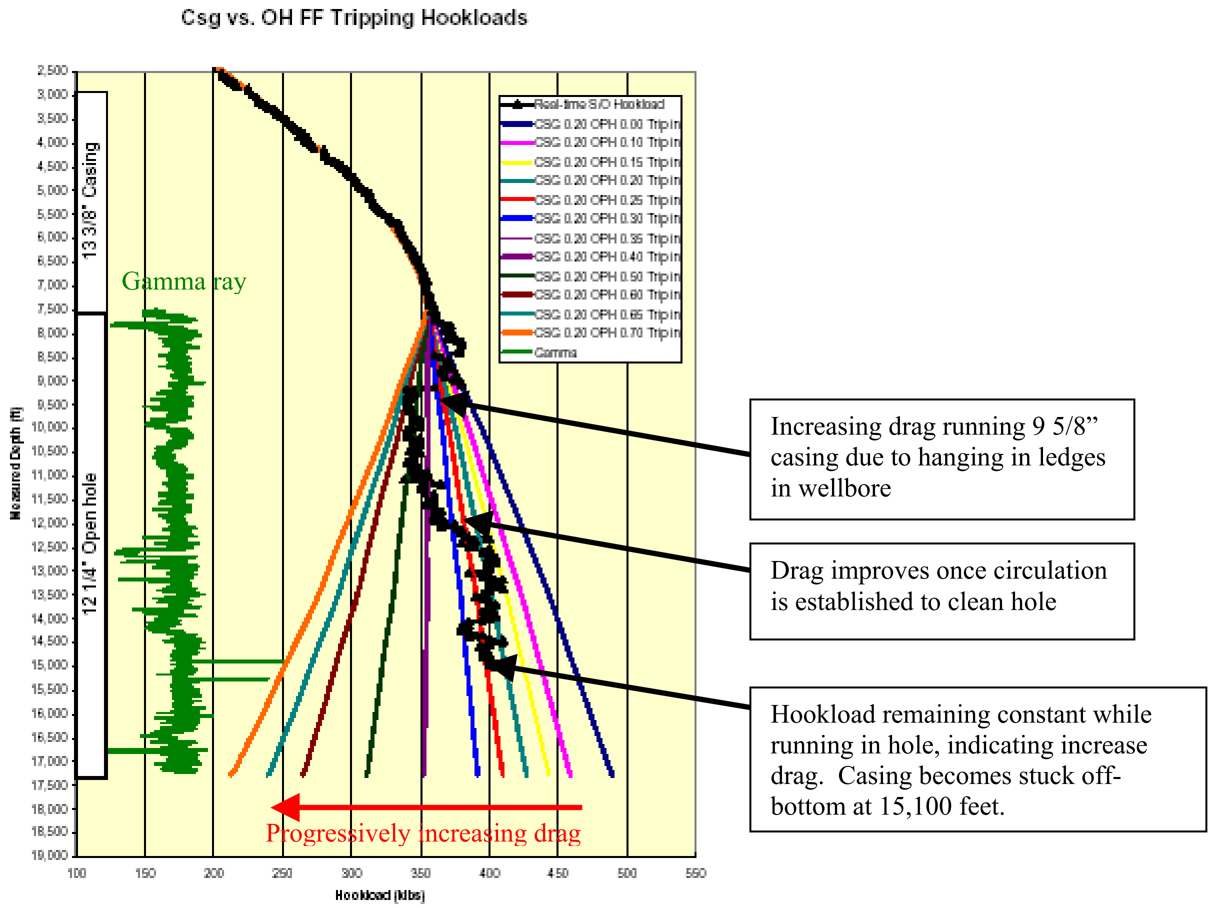

Figure 14- Torque Chart – mud lubricants evaluation