# Automated Monitoring of Torque and Drag in Real-time

***Master Thesis***

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Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbständig und ohne fremde Hilfe verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und mich auch sonst keiner unerlaubten Hilfsmittel bedient habe.

# AFFIDAVIT

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

9.03.2009

(Date)

(Philipp Zöllner)

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# Abstract

Torque and drag are two parameters in the well construction process that deserve special concern, as they are ever-present factors during drilling and tripping operations. Especially today's increase in drilling and completing highly inclined and extended reach wells, often results in situations where these drilling parameters are pushed to their limits.

Everyone involved in the well construction process needs to be aware of the challenges resulting from excessive torque and drag. Due to the difficult well paths to be drilled, stuck and lost pipe situations may be encountered more easily, but need to be avoided at all costs.

As a consequence, detailed monitoring of torque and drag is a key element in the successful construction of a planned well path. Although this is already done in an excessive manner, the important parameters to enable a reduction of lost and hidden lost time are still taken manually and inconsistently. These parameters that need to be tracked are hook load, while drilling and running in respectively out of the hole, as well as torque, during pipe rotation. Trend analyses, based on this manually process, for wellbore health status evaluation, are still uncommon.

In order to improve the monitoring process, it is essential to make use of the mudlogging sensor data combined with an automated algorithm, recognizing the ongoing rig operations. An improved approach of tracking torque and drag in real-time, as well as the newly developed software application for this purpose, are described throughout this thesis. In addition, already available monitoring approaches have been evaluated and discussed, based on their advantages and limitations.

The main principle behind the used technique is a hook load and torque comparison of actual versus planned (simulated) values. These actual values are calculated for different operations (drilling, tripping, running casing, etc.) on a stand per stand basis and plotted over the measured depth of the bit. The resulting trend analysis that can be performed, allows identification of upcoming critical situations at an early stage. Based on this information, the drilling crew is able to react immediately by executing the appropriate counteractions, and expensive lost time situations can be prevented thereof. In advance, wellbore conditioning operations can be optimized based on the quality of the wellbore, which is evaluated without interfering ongoing rig operations.

The main goals were to keep this new automated real-time approach as simple as possible and to focus on visualization methods the office as well as the field personnel are used to. Wrong assumptions and misinterpretations due to new visualization techniques had to be avoided any time.

# Kurzfassung

Zwei Parameter, die während des Bohrprozesses spezielle Aufmerksamkeit benötigen, sind Torque und Drag. Der Grund hierfür liegt darin, dass diese Bohrparameter ständig präsent sind, sei es ob gebohrt, verrohrt, ein- oder ausgebaut wird. Da immer kompliziertere Bohrpfade benötigt werden um eine Lagerstätte zu erschließen, werden speziell diese beiden Bohrparameter nahe an die Grenzen des technisch möglichen gebracht.

Es ist daher essentiell, dass das gesamte Team, welches für die erfolgreiche Abteufung von stark abgelenkten oder sogenannten 'Extended Reach' Bohrungen zuständig ist, sich über die Folgen von überschrittenen Werten von Torque und Drag im Klaren ist. Auf Grund dieser schwierigen Bohrpfade sind Situationen, in welchen Rohre durch Steckenbleiben verloren gehen, schneller erreicht als bei vertikalen Bohrungen. Da mit den eben beschriebenen Situationen hohe Kosten verbunden sind, liegt das Hauptaugenmerk auf ihrer vehementen Vermeidung.

Daraus ergibt sich, dass die Parameter Torque und Drag auf genaue Weise verfolgt werden müssen. Obwohl dies bereits in umfangreichem Maße durchgeführt wird, werden die benötigten Werte oft noch händisch ermittelt und manuell in Graphen eingetragen. Der dadurch entstehende Mehraufwand sowie das notwendige Training resultieren in unregelmäßigen Arbeitsschritten. Parameter, welche für Torque und Drag verfolgt werden müssen, sind die Hakenlast während des Bohrens und des Ein- und Ausbauens sowie das Drehmoment während der Rotation des Meißels. Eine auf diesen Werten basierende Trendanalyse um die Qualität und den Zustand des Bohrloches zu ermitteln ist im Kommen aber noch nicht alltäglich.

Um das Verfolgen der eben erwähnten Parameter in Echtzeit zu ermöglichen und so die Überwachung auf eine höhere Ebene zu bringen, wurde im Rahmen dieser Arbeit ein Projekt durchgeführt, bei welchem eine Software Applikation zu diesem Zwecke entwickelt werden sollte. Basierend auf den Echtzeitdaten, welche vom Mudlogger an der Bohrstelle gemessen werden, sowie der Einbindung einer automatischen 'Operations Recognition' sollte dies ermöglicht werden. Die genauen Entwicklungsschritte sowie die Vorteile dieser verbesserten Methode werden in der Arbeit beschrieben. Des Weiteren wurden bereits vorhandene Methoden evaluiert und kritisch auf Vor- und Nachteile geprüft.

Das Kernstück der entwickelten Applikation ist die graphische Darstellung von Hakenlast bzw. Drehmoment aufgetragen über die Meißeltiefe. Bei den durchgeführten Trendanalysen werden die mittels Simulator errechneten und geplanten Kurven mit den aktuellen Echtzeitwerten verglichen. Speziell daran ist die verwendete 'Operations Recognition', welche es ermöglicht zwischen den einzelnen unterschiedlichen Operationen (Bohren, Ein- und Ausbau von Gestänge, Verrohen, etc.) automatisch zu differenzieren.

Die Überlagerung von aktuellen und geplanten Punkten bzw. Kurven ermöglicht es mögliche kritische Situationen früher zu erkennen. Daraus ergibt sich der Vorteil, dass die Bohrmannschaft früher reagieren und eventuelle Gegenmaßnahmen setzen kann um so kostenintensive Folgewirkungen zu vermeiden. Weiters können die Trendanalysen zur Optimierung sowie Reduzierung der Bohrlochbehandlungszeiten herangezogen werden. Der dabei andauernde Bohrprozess wird währenddessen weder beeinflusst noch gestört.

Die wichtigsten Vorgaben lagen darin, die Anwendung so einfach wie möglich zu halten sowie den Fokus auf eine Visualisierungsmethode zu richten, die für Ingenieure sowie Bohrpersonal vertrautes Terrain darstellen. Missinterpretationen und falsche Annahmen auf Grund von mehrdeutigen Darstellungsmöglichkeiten mussten dabei vermieden werden.

# Real-time Monitoring of Torque and Drag

This chapter discusses current real-time monitoring approaches of torque and drag (T&D) as well as friction factor (FF). It further gives an overview on the different possibilities on how to measure and track these parameters and addresses the weak points of such systems. In addition, a separate chapter deals with the necessary changes needed in order to modernize T&D software packages which are based on different friction factor types and drill string models.

## Introduction

Because today more difficult wells are drilled as compared to the past, most of the drilling parameters are pushed to their limits during drilling operations. This is especially the case for highly deviated or extended reach wells where for example torque, drag, wellbore hydraulics and cuttings transport are of major concern. This thesis primarily deals with the parameters torque and drag as well as the resulting friction factor.

These two parameters have a major impact on the planning of a well because with improper T&D management, the desired well may not be able to be drilled to total depth. As a consequence, proper T&D planning is compulsory when constructing an inclined well and current methods of drilling performance optimization need to be improved. Several possibilities for friction reduction have been developed up to now, such as non-rotating drill pipe protectors, specialized drill pipes and new mud systems utilizing lubricants.

In addition to these mechanical methods, a pre-calculation of the expected hook load and surface torque is performed. The calculations are based on offset well data from which different expected friction factors and mud weights are used. The results are then shown on a load versus depth plot which is used as a comparison to the current hook load and torque that is observed at the rig.

The figures below show two different possibilities of such pre-calculated hook load curves, so-called ‘tension comparisons’. Both methods are based on an assumed friction factor evaluated from previous wells in the same geological area. The first method is an incremental approach where the hook load (respectively torque) is calculated from bottom to top in incremental steps of 30 or 50 meters (representing a section or a stand of the drill string).

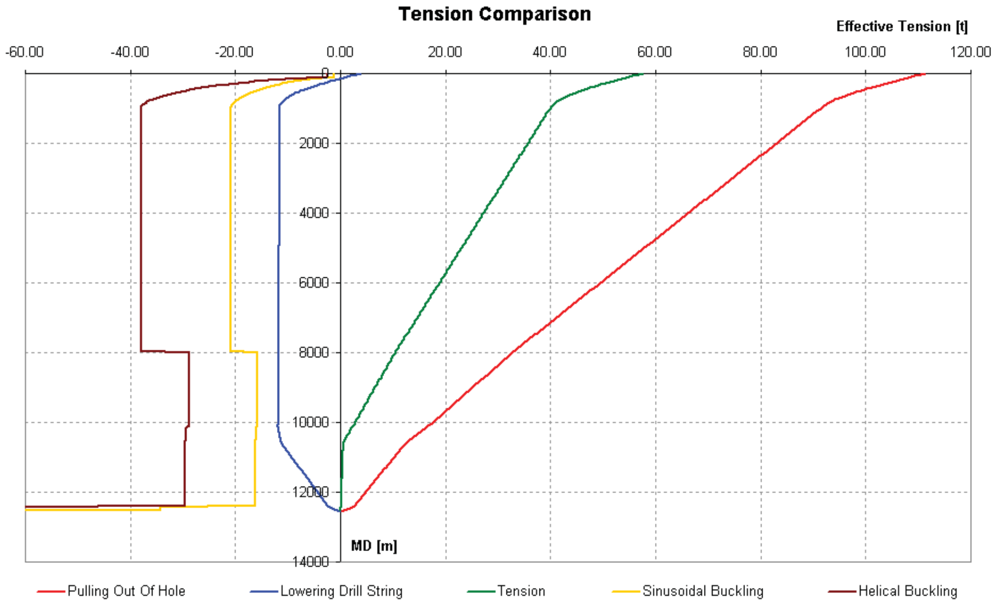


Figure 1: Tension comparison

Such an analysis is done for the operations ‘Running In Hole’ (RIH) and ‘Pulling Out Of Hole’ (POOH) as well as for ‘Rotating Off Bottom’ (ROB). In addition, the sinusoidal and helical buckling curves are calculated to ensure that the proposed well path can be drilled and completed with the selected drill string equipment. During the planning of a well, it is necessary to model several drilling parameters such as the trajectory (inclination, azimuth) as well as drill pipe and BHA components (heavy-weight drill pipes, drill collars, etc.) in order to size the rig correctly and to optimize the drill string accordingly. The outcome should assure that the final well design is feasible.

Another possibility is to calculate the surface hook load (respectively torque) for each depth with the necessary equations stated in the Appendix. The results are again plotted over depth for different expected friction factors (Figure 2).

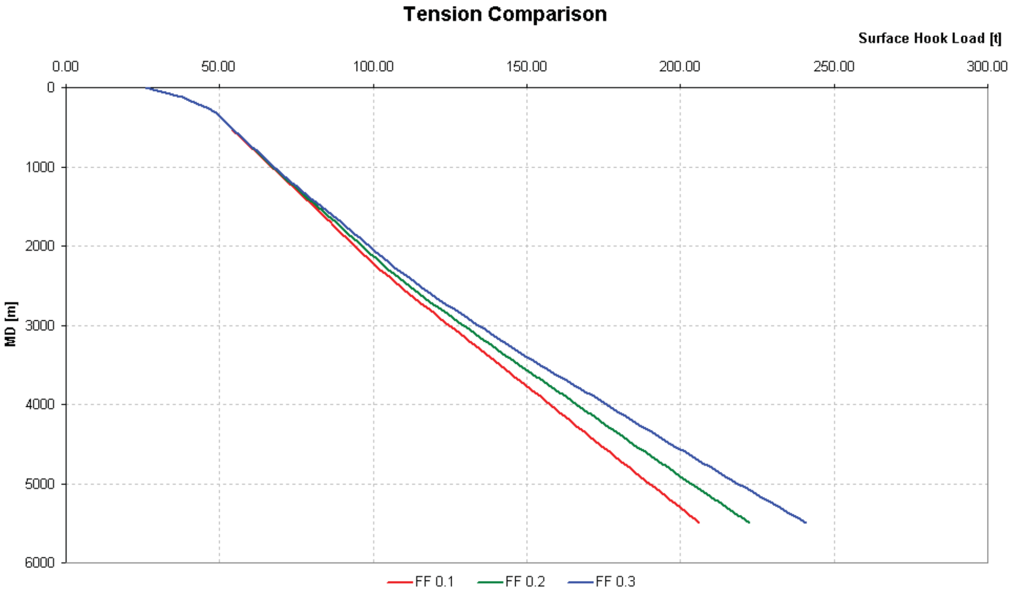


Figure 2: Surface hook load curves calculated in the planning phase (for POOH)

Throughout recent years it has become increasingly obvious that T&D are the two parameters where efforts need to be focused in order to improve drilling performance and to extend the reach of highly deviated wellbores. Although many sensors are used at the rig site to measure the process of constructing a well, it is common to leave these data unused instead of trying to improve operations with it.

The following chapters describe how to enhance T&D measurements with the use of real-time data. Furthermore, the state-of-the-art methods of real-time T&D monitoring are presented. Finally a separate chapter deals with the problems and limitations of such automated drilling systems and T&D modeling in general.

# Current Real-time Monitoring Approaches

## *'On-Line T&D' – Real-time Friction Factor Monitoring*

Several years ago, a new method of monitoring T&D was introduced to the oil industry[1, 2]. In contrast to the 'old' method of using only pre-calculated curves, this system determines two different types of real-time friction factors. The exact method of how this is accomplished is described throughout this chapter. In general, the system works by the use of the downhole-measured weight on bit (DWOB) and torque on bit (DTOB) coupled with surface load measurements.

The results, together with the real-time measured data, are then presented graphically and numerically on a computer screen. This allows the driller and drilling supervisors to get direct information on the current wellbore condition as well as enabling them to predict upcoming critical situations at an earlier stage. The main purpose of being able to take counteractions as soon as possible is therefore fulfilled, which should allow rig operations to be performed to the limits of the drill string load capacities.

The method described up to now has been developed as part of a series of performance enhancement tools and is included in the 'On-Line T&D' software package provided by an oilfield service company. This technique is based on the calculation of a force and torque equilibrium along the drill string that is placed in a certain borehole. In addition, all the forces and torques acting on respectively within the drill string are determined. These calculations are based on the use of measured surface data and downhole values as input parameters.

For the equilibrium calculation procedure, the drill string needs to be made up of short elements. These segments, with a length of 10 meters, have calculation points on each end, so-called 'knots'. The procedure starts at the bottom of the string with the lower boundary conditions. As already mentioned, downhole WOB and TOB information needs to be available. This information is required in order to start calculations at the bit. With these two parameters, all the required properties can be determined at each knot. The calculation algorithm is then repeated with a changed friction factor until the calculated loads at the final (upper-most) knot equal the values measured at the surface.

In general, this technique works for four operation modes which are Drilling, ROB, 'Picking Up' and 'Slacking Off'.

'Picking Up' (PU) and 'Slacking Off' (SO) are simply other expressions for the operations RIH and POOH which are explained in the Appendix. It is important to note, that during such operations the drill string is just moved in axial direction without any rotation. The terms 'Picking Up' and 'Slacking Off' weights are used very commonly in the oilfield business, as these weights indicate if there is a lot of drag existing due to bad wellbore condition or improper design of specific parameters. The greatest importance of these two operations occurs at the beginning of the string movement. As described in the Appendix, the static friction factor is in most cases higher than the kinetic one. This means that whenever the string is intended to be moved, the weight will be at a minimum or at a maximum, depending on the direction. When the pipe is run into the hole, the higher friction factor will result in less weight for the hook to carry. In the beginning of a drill string raising process, the static FF will cause a higher over pull compared to the kinetic one.

During 'Rotating Off Bottom', the drill string is just rotated without any movement in axial direction. As there is no absolute velocity in the vertical direction existing during such operations, but instead in a rotational direction, the drag due to frictional forces can be neglected. The consequence of this phenomenon is that in the ideal case, just pure tension is acting without any over pull or slack off. The ROB hook load curve can therefore be plotted as a centre line between different FF curves for RIH and POOH.

Especially for drilling operations, DWOB and DTOB information needs to be available. For RIH, POOH and ROB, the lower boundary conditions can be set to zero as the bit is off bottom and no forces and moments will be acting on it. Nevertheless, the upper boundary conditions, the real-time measured sensor data, need to be evaluated for all operation modes. This information needs to consist of surface torque, hook load, the rotations per minute of the string and the calculated rate of penetration.

The output of the iteration algorithm described above is the calculation of two different friction factors:

### Global Friction Factor

The global or wellbore friction factor is, as its name indicates, valid for the complete well. This is essentially the same as described in the Introduction. As there is no need of real-time data to get a friction factor for a complete section of a well, it is quite easy to calculate. The simple torque and drag equations can be used in order to back-calculate the friction factor with the use of historic surface sensor data measured during already drilled wells.

The real-time method shown in the next figure calculates a new FF valid for the total hole whenever a new step in the analyzing process starts. This means that with each new step, the old friction factors are not valid anymore and therefore not required for further analysis. Any changes in the frictional environment are not over-expressed because of the fact that the calculated FF is averaged over the total wellbore. As a consequence the true interaction between the drill string and the borehole wall is determined.

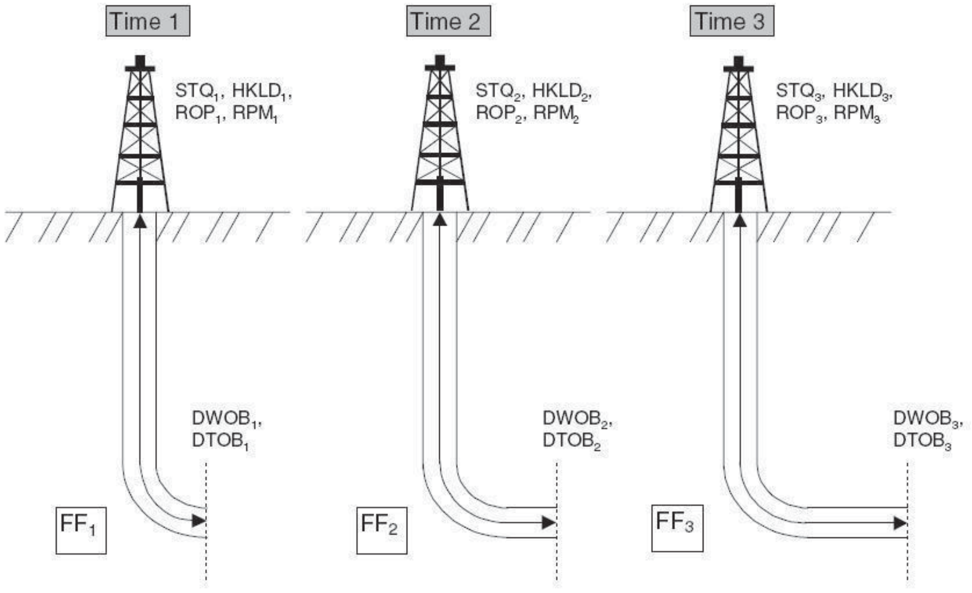


Figure 3: Global friction factor [1]

When using an expected friction factor from offset well data for torque and drag calculations, the responsible drilling engineer needs to be very careful. Assuming friction factors can always lead to inaccurate results because the basic equations do only take the pure mechanical friction into account. This means that the friction factor is not only dependent on the formations drilled, but also on the rheology of the mud as well as the condition of the wellbore. Wellbore condition has a major impact on the actual friction factor, which can be completely different compared to the one assumed by experience. Factors influencing the 'health' of a borehole are the occurrence of key seats, ledges, wash-outs and cavings. All these parameters together need to be considered when talking about the actual friction factor, the so-called 'pseudo friction factor', in a well.

Other contributors to the true mechanical friction between borehole wall and drill string are listed below:

- Stiffness of the tubular components
- Viscous drag of the drilling fluids
- Presence of stabilizers and/or centralizers
- Formation types
- Differential pipe sticking due to pore pressure
- Loss of circulation
- Micro-tortuosity (wellbore spiraling)

Although the global friction factor is easy to back-calculate out of surface measured data, the determination of the real friction factor between the drill string and borehole wall is not that simple. As there are no FF-logging methods available, one common approach is the already mentioned friction factor estimation for the total well. For more advanced torque and drag calculations, for example when a mass-spring model is used for drill string modeling, a friction factor for each segment of the wellbore needs to be available. This type is explained in the next chapter.

### Incremental Friction Factor

In contrast to the global friction factor, the incremental one is much more difficult to calculate. The first step in the algorithm is the determination of a friction factor for the top hole section (indicated by $FF_1$ in Figure 4) which goes down to the starting point of the FF-log. When the analysis starts, a friction factor is calculated in incremental steps. This means that for a certain interval drilled, a distinct friction factor is evaluated with the algorithm described before. Whenever a new interval is drilled, the previously determined friction factors are applied for the rest of the hole and a new incremental one is calculated. In this case the friction factor in the upper part of the borehole remains constant.

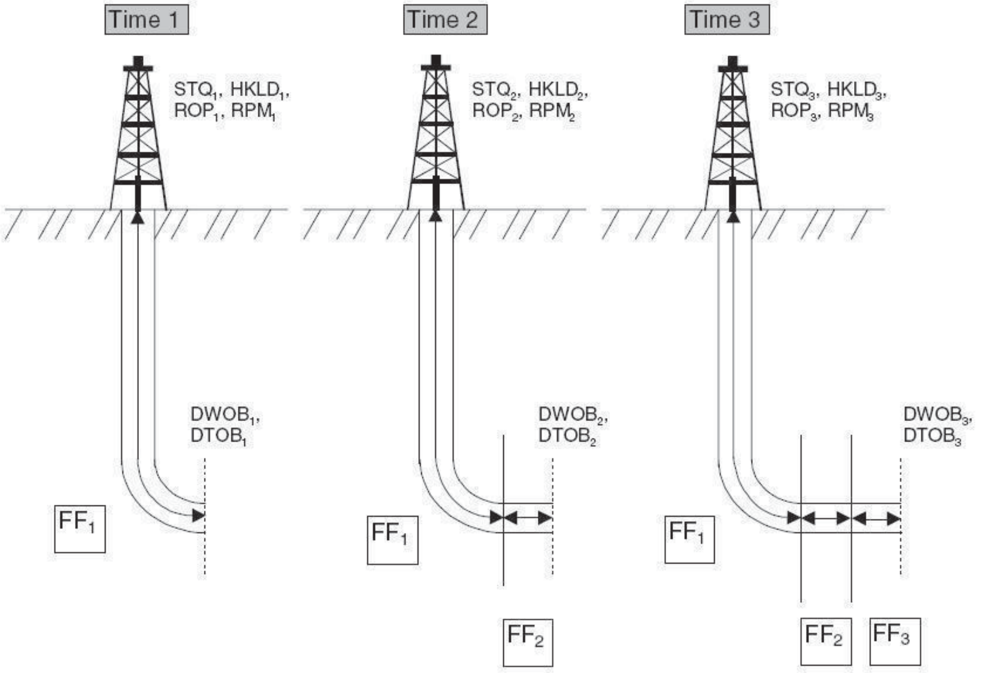


Figure 4: Incremental friction factor [1]

Figure 4 indicates that the friction factors calculated with the incremental method are only valid for one certain small interval of the well. Due to the special calculation procedure, any change in the frictional environment of upper sections, results in an over expression of the currently calculated friction factor. As a consequence, the higher actual friction factor value makes it more obvious for the user that there is a problem arising. Unfortunately, the incremental method does not show where such a change in frictional environment originates along the wellbore, which is a big disadvantage.

Case studies conducted by the international service company developing this software have shown that it is necessary to average the incremental friction factor over a certain depth interval. The reason for this is to compensate the problem of data fluctuations due to drill string vibrations and sensor inaccuracies. The normal interval for the incremental calculation algorithm is about one meter long as it depends on the frequency of the downhole data set that is transported to the surface. The problem with the results is that a compromise between high density FF-log and clear visible friction factor trends needs to be found.

The way to present the results to the driller and the responsible rig personnel is shown in Figure 5.

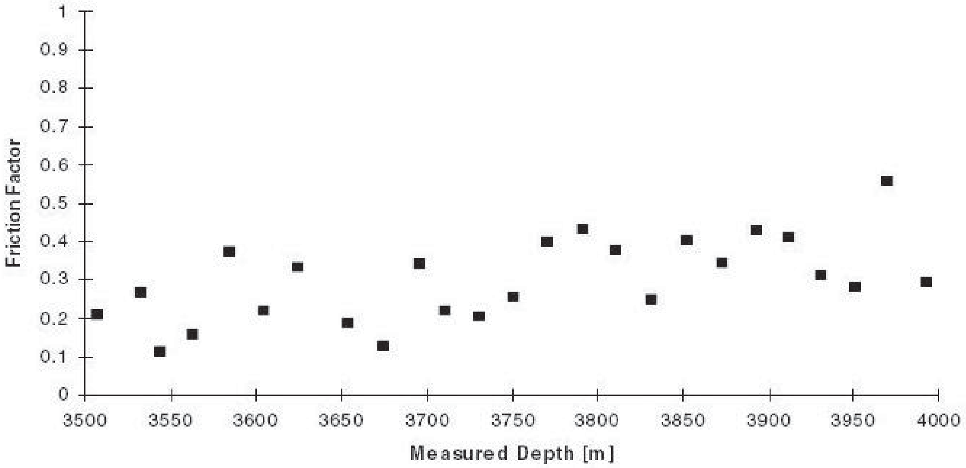


Figure 5: Averaged incremental friction factor over depth [1]

For the global friction factor visualization, there is no need of averaging as the sensor fluctuations do only have a significant influence on the incremental method.

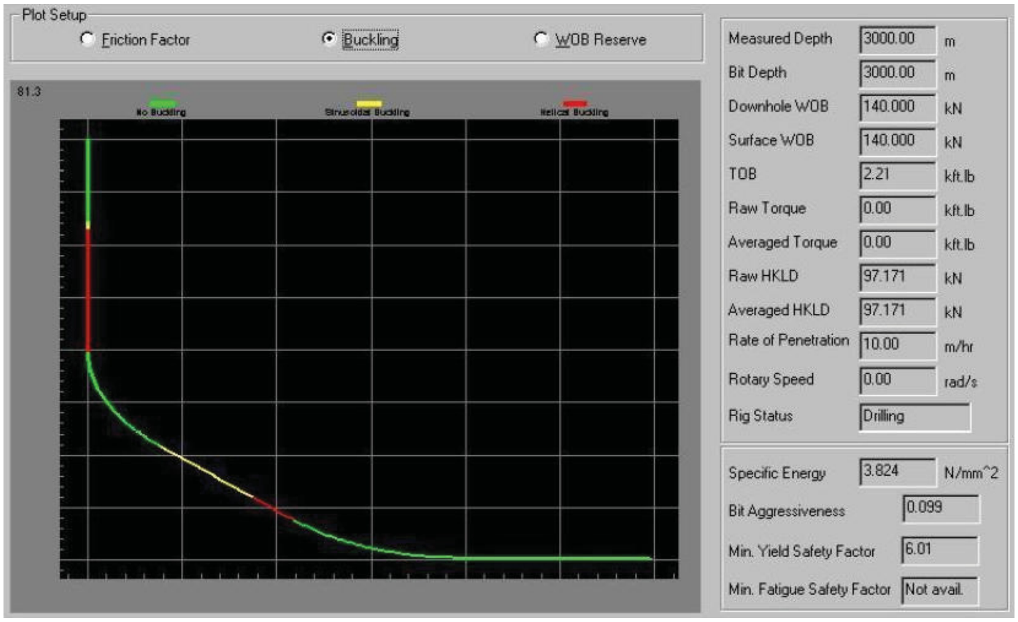
## Algorithm for Sliding Drilling

The algorithm for sliding drilling differs from the one in rotating mode in one specific way. A special method is applied with an own sliding friction factor calculation. During such operations the iteration process is stopped when the measured and calculated hook load are equal. This differs from the algorithm used while in rotating mode as the axial velocity is negligible compared to the velocity in rotational direction. As a consequence, the iterations are stopped when the measured torque matches the calculated one.

## Additional Applications

There are several other applications included in this real-time monitoring approach which result from the algorithm described. The two important ones are the so-called 'Buckling Mode' and the 'WOB Reserve Until Buckling'. These are two further visualization possibilities which should help the driller, together with the friction factor plot, to go closer to the operating limits.

The first method, the 'Buckling Mode', visualizes the current buckling situation of the drill string. Due to all the calculations mentioned with the friction factor determination, the complete load and torque distribution on and within the string is known. As Figure 6 indicates, the responsible drilling staff gets a graphical output for every calculation interval where the occurrence and type of buckling is displayed over the well path.



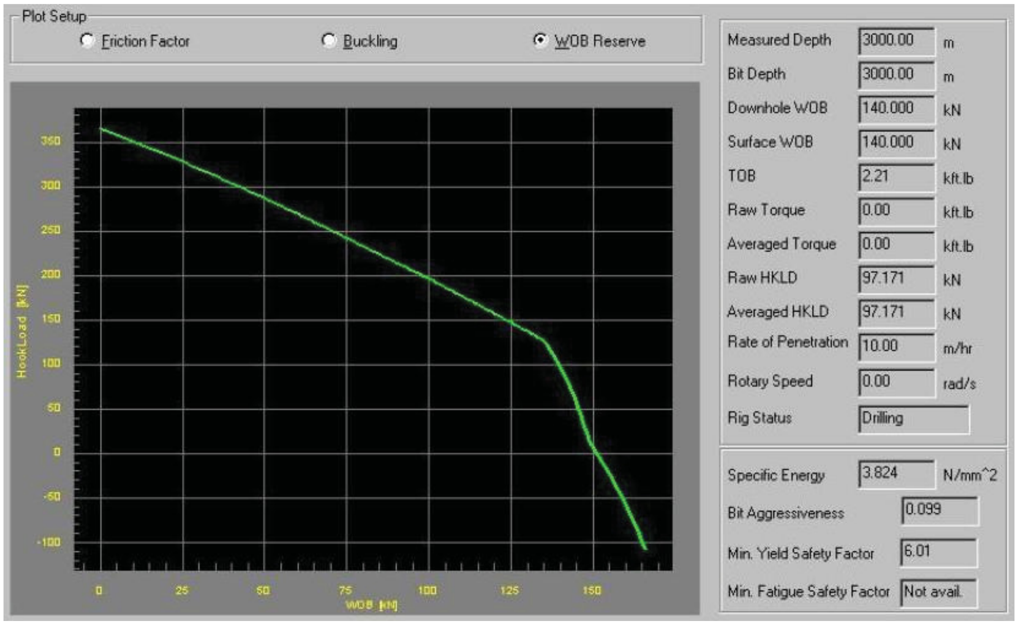
Measured Depth 3000.00 m
Bit Depth 3000.00 m
Downhole WOB 140.000 kN
Surface WOB 140.000 kN
TOB 2.21 kft.lb
Raw Torque 0.00 kft.lb
Averaged Torque 0.00 kft.lb
Raw HKLD 97.171 kN
Averaged HKLD 97.171 kN
Rate of Penetration 10.00 m/hr
Rotary Speed 0.00 rad/s
Rig Status Drilling
Specific Energy 3.824 N/mm^2
Bit Aggressiveness 0.099
Min. Yield Safety Factor 6.01
Min. Fatigue Safety Factor Not avail.

Figure 6: Buckling displayed over the well path ('Buckling Mode') [2]

Green areas indicate that there is no tendency of the drill string to buckle, whereas yellow sections should warn the user of the occurrence of sinusoidal buckling. Helical buckling is represented with a red color. This graphical illustration should allow the driller to react when any part of the drill string is likely to be buckled.

The second application, the ‘WOB Reserve Until Buckling’, should allow optimization of the weight transfer to the bit. This is done by a graphical illustration of the hook load over the weight on bit (WOB). This plot (Figure 7) is the result of a ‘WOB Reserve Until Buckling’ calculation and shows the additional WOB that is created when the hook load is lowered for the well path shown in the previous figure. The curve in this plot shows that any additional lowering of the hook load below a value of about 125 kN would create only minimal increase in WOB. Furthermore, the string would start to buckle or even to lock up.

If the drill string would be rotated, the curve in Figure 7 would be a straight line as the drag would be missing. In the example used, the rotary speed is zero which means that the resulting non-rotating graph runs against an asymptote with increasing weight on bit. The asymptote indicates the lock-up effect if the hook load is decreased too much.



○ Friction Factor ○ Buckling ● WOB Reserve

Measured Depth 3000.00 m
Bit Depth 3000.00 m
Downhole WOB 140.000 kN
Surface WOB 140.000 kN
TOB 2.21 kft.lb
Raw Torque 0.00 kft.lb
Averaged Torque 0.00 kft.lb
Raw HKLD 97.171 kN
Averaged HKLD 97.171 kN
Rate of Penetration 10.00 m/hr
Rotary Speed 0.00 rad/s
Rig Status Drilling

Specific Energy 3.824 N/mm^2
Bit Aggressiveness 0.099
Min. Yield Safety Factor 6.01
Min. Fatigue Safety Factor Not avail.

Figure 7: ‘WOB Reserve Until Buckling’ [2]

## Conclusions on ‘On-Line T&D’

Generally it needs to be stated, that this approach is one of few real-time software packages found during the first phase of this thesis, where it was the aim to evaluate the state of the art in T&D monitoring. Several other real-time tools used to monitor these two critical parameters simply plot the actual hook load values over the measured depth of the hole without any additional algorithm or data processing acting behind the visualization. The ‘On-Line T&D’ tool seems to be a smart tool as it includes several helpful features but there are also limitations that have to be addressed.

One example of these limitations is certainly the need for the two downhole channels (WOB and TOB) for the special calculation procedure. Because these two channels are a prerequisite for getting calculation points, especially during drilling operations, it is necessary to measure these parameters to have the total functionality included. In contrast to surface-measured channels, these two channels will not always be available as there is not always a tool included in the BHA to measure downhole values. The absence of these parameters would result in a huge usability limitation of the tool.

Another point that needs to be discussed is the visualization method of the results. The ‘WOB Reserve Until Buckling’ and ‘Buckling Mode’ features seem to be very useful ways to present the calculation results to the drillers and responsible field personnel. Having upcoming problems while drilling and tripping presented in such a graphical way can help them to react as early as possible and to conduct correct counteractions.

Nevertheless, the friction factor visualization method seems to be quite complicated for personnel that are not used to getting torque and drag calculations presented in such a graphical way. As a consequence, it could easily lead to misinterpretations. Especially the need of both friction factor types and the necessary averaging procedure seems to be a more complicated way compared to hook load versus depth curves. Generally the user has to decide on his/her own if the FF versus depth plot is a proper way to get the results visualized. Nevertheless, the user has to know what trends in friction factor curves mean, especially as the two types differ from each other and the incremental one has the averaging functionality included.

Another point to be addressed concerns the operations differentiation between RIH and POOH. The correct definition of these two parameters includes only movement of the string without any rotation and pumping. Unfortunately, it is not always the case that a string is simply run in or out of the hole. Concerning ‘On-Line T&D’, it is not clear how the algorithm works while reaming up and down before making a drilling connection, while tripping with pumps on, or while wellbore conditioning. There was no clear statement of how the results are visualized for other operations than drilling (rotary and sliding) and simple running in and out of the hole. It is possible that during such operations no points are calculated or that simply no differentiation between the completely different types is made. As described earlier, friction factors for a rotated drill string are generally lower compared to ones without rotation. As a consequence, a clear differentiation has to be made for these two types and visualized in different ways.

Finally it needs to be mentioned that there was no historical mode for this tool described in the literature. For evaluation and analysis of previously drilled wells it would be great to have such a feature included. Planning engineers could use this functionality to process several wells in the same field as the one to be drilled and use the results for their planning purpose. It is possible that this feature is included in the software package but it was not described in the accompanying literature.

## *Other Company Solutions*

A second real-time T&D monitoring approach described is called 'Drilltronics' [3]. The key element of this model is the same as the one with 'On-Line T&D' which is based on the continuous updating of real-time measured data. This methodology uses 'Kalman' filtering techniques which provide a calibrated model that can be compared to the real-time data and allows quick detection of unwanted occurrences. The same principle as with the method described before is used to calculate the actual friction factor in the wellbore. During several operations, downhole weight and torque on bit are used to start calculations at the bottom. When the actual values for hook load or torque at the surface match the calculated ones, with an assumed friction factor, the algorithm is stopped.

T&D monitoring can also be used to optimize completion string installations. Although it is of special importance during a well that is being drilled to total depth, the possibility of being not able to run such special tools does exist. Especially in open hole horizontal wells where additional challenges may come up (e.g.: gravel pack assemblies) proper T&D management is essential. Furthermore, downhole completion hardware is not as durable as is drill pipe or drilling BHA hardware. Newly developed drilling technologies (Rotary Steerable System, Measurement While Drilling, real-time T&D modeling software, etc.) allow the construction of more complicated wells where additional loads and stresses are acting on the tubular assemblies. These forces may not be a problem for the drill string, but need to be evaluated and understood prior to designing a completion string. Another fact concerning completion strings is that it is not possible to rotate or float the equipment to final target. If the string cannot be delivered down to the bottom of the well, the drilling investment is partially or even entirely compromised.

## *‘PRS Test’*

The ‘PRS Test’ was a test newly developed for the drilling of several extended reach wells in the North Sea [4]. As especially for extended reach drilling projects the monitoring of friction and its influence on the success of the project are essential, following test was devised. During the following operations, the crew at the rig had to manually record the actual surface hook load and torque:

- During tripping in and out at the casing shoe
- After a stand was drilled down
- During picking up the string
- During slacking off the string
- While rotating off bottom

Every operation of the ‘P (Picking Up), R (Rotate), S (Slacking Off) Test’ had to be performed with and without the pumps running.

Figure 8 is a plot of time versus depth and shows a time log section of 24 minutes where a ‘PRS Test’ was performed while drilling a well in ‘Captain Field’. The interval of the test is marked with green lines and is divided into its three parts.

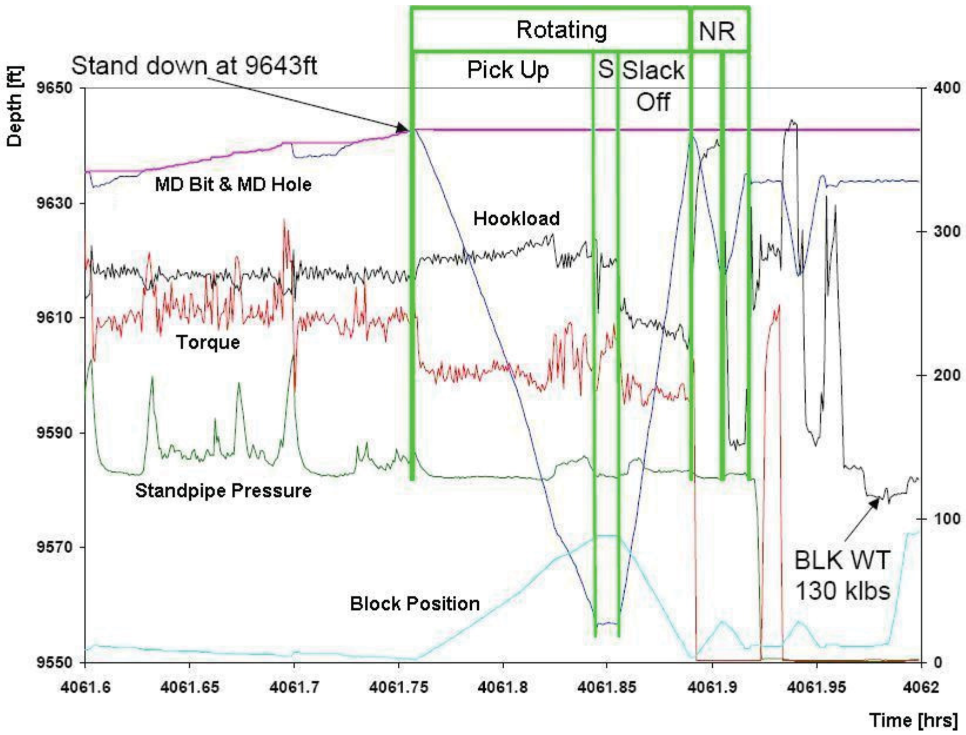


Figure 8: ‘PRS-Test’ developed for extended reach drilling [4]

In this special example, the test was performed for about ten minutes after a stand was drilled down to a depth of 9643 ft. In the beginning of the record, the bit was moved off bottom, which is indicated by a decrease in bit depth and an increase in the height of the block. At the end of this 'Pick Up' interval, the hook load slightly increased and decreased again as the block movement was slowed down. The standpipe pressure stayed constant for the whole interval, whereas the torque channel showed fluctuations, especially in the end. The next stage of the test was to hold the string stationary, which resulted in lower hook load and continued fluctuating torque. During slacking off with rotation, the hook load and torque dropped further as friction works against the lowering movement. Finally, the rotation of the string was stopped when moving the pipe. This operation resulted in much higher drag, whereas torque dropped to zero.

As already mentioned, the test had to be performed during several operations in a very consistent manner to assure proper T&D monitoring. The next figure shows a comparison of a T&D prediction for an extended reach well and the actual values gathered during the 'PRS Test'. A slight discrepancy can be clearly seen between these two types of analysis.

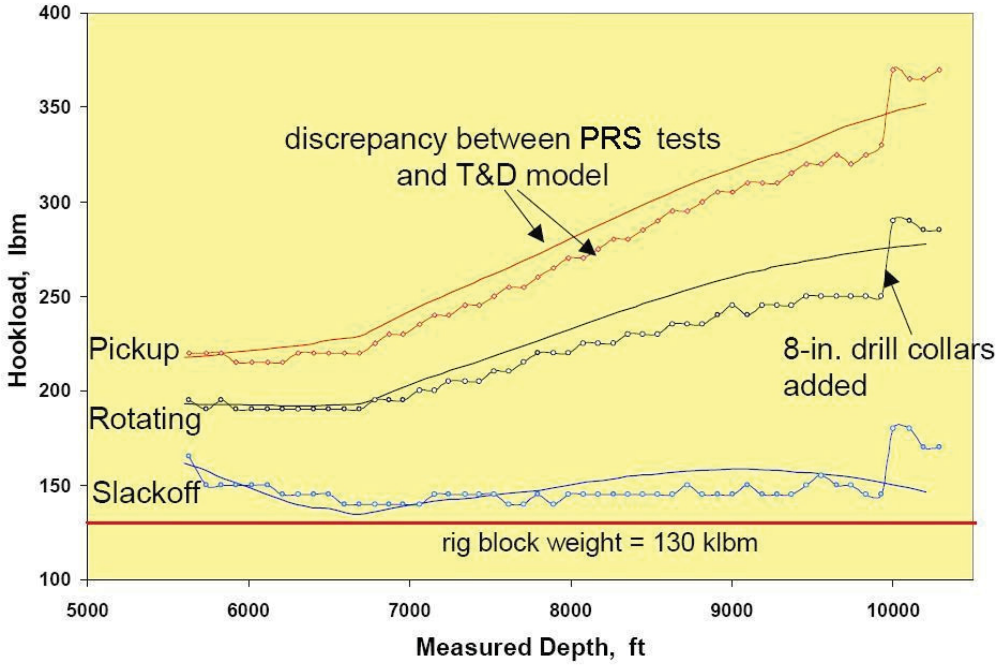


Figure 9: Comparison of 'PRS Test' and predicted hook load [4]

### Conclusions on ‘PRS Test’

Several problems arising with such a test are obvious and need to be discussed. Besides the most obvious factor, the time it takes to conduct the test in a consistent manner, several other factors can influence the effectiveness of the project:

- Insufficient training of the rig personnel
- No continuity in measuring data at the rig
- Failure of not using measured data
- No clear baseline established

It is clear that making measurements of sufficient quantity as is required for ‘PRS Tests’ takes a lot of rig time. The time needed to make such a test is about the same as for a directional survey, but tends to take longer. According to experience, it is necessary to take PRS readings after every drilled stand, to assure proper outcomes for T&D monitoring. Unfortunately, the temptation to skip tests or to take them only after every third stand is very high. There is always a tendency to eliminate time-consuming measurements to reduce rig time. This may result in data curves where trends cannot be identified anymore. Incorrect conclusions could be made by the responsible drilling engineer, based on improper measurement procedures. The curves and trend comparisons in Figure 9 for example, could lead an inexperienced engineer to wrong assumptions. The previously-mentioned discrepancy shows lower hook load values for the PRS readings than for the normal (expected) curves. As both, the RIH and POOH curves, are lower the discrepancy must have its origin in improperly calculated simulated curves or a lack of continuity in the conduction of the ‘PRS Tests’.

It is therefore necessary to improve any lack of continuity and make sure that in practice every rig operation is monitored by trained rig personnel. Communication failures between different shifts may also lead to difficulties in diagnosing key problems. The problem of letting different people perform the tests in different intervals also needs to be discussed. Some crews might even skip tests to have time for other operations. As a consequence, a clear baseline needs to be established to assure a perfect result that can be worked with.

The last point that needs to be addressed is the fact that signs of problems are often just read without any reactions taken. It is a common practice in the petroleum industry to use sensors for taking many measurements at the rig. Although nearly every operation is recorded and stored in a database, the available data is not further used for optimization.

Summarizing all the facts and problems described in the paragraphs above, it seems that there are too many issues coming up when using the ‘PRS Test’ method to track

T&D. Not only the time it takes to make the tests is a major issue, but there is also the problem that the field personnel have to take the readings. The accuracy and continuity of the results depend on the attitude and training of the people working at the rig site. As it is a time-consuming issue to perform the tests properly, the results will always suffer from a lack of continuity.

# Parameters influencing T&D Design

This chapter deals with the limitations of current T&D models that are commonly used in the planning phase and to predict and prevent critical situations during drilling and completion. It should further give an overview on the different models and parameters influencing T&D calculations. According to the literature, T&D software has already existed for more than 20 years but some confusion still exists over the validity of the models used to characterize drilling operations [5]. The mathematical models behind all the T&D software packages available, is still the same since its original inception. Although these models did not change at all, the software user interfaces have improved with the significant improvements in computer hardware and processor power during the last few years.

Another section of this chapter will deal with the practical limitations of the existing T&D models and focuses on the mistakes made by the user due to misinterpretations.

These core drill string models already mentioned are the soft-string and the stiff-string models and will be discussed in detail.

## *Soft-String Model*

The soft-string model is a very basic model and underlies the easy equations stated in the Appendix (chapter Friction Eq.2 – 13). It is called ‘soft’ because it ignores any effects caused by tubular stiffness. This means that the model assumes the pipe to be a heavy cable that is lying along the wellbore which results in the further assumption that any tension and torque in axial direction is supported by the drill string and all the contact forces are supported by the wellbore.

As already mentioned, the model underlies the very basic equations which take only gravity and frictional drag into account. Equation 5 for example states the formula to calculate the normal force N in a very basic manner. This equation is modified for the soft-string model to account not only for an inclined surface but also for any change in azimuth.

As a consequence, N ( $F_N$ ) can be calculated the following:

$$F_N = \sqrt{(F_G \cdot \cos\theta \cdot \Delta\phi \cdot \sin\theta)^2 + (F_G \cdot \cos\theta \cdot \Delta\phi + F_G \cdot \sin\theta)^2} \qquad \text{(Eq.1)}$$

Where $\Delta\phi$ = Change in azimuth [°]

Where $N$ or $F_N$ = Normal force [N]

Where $F_G$ = Gravitational force [N]

Where $\theta$ = Inclination [°]

The basic idea and procedure of the common T&D calculations during planning phases have already been described in the chapter Introduction. The next paragraph describes the procedure and assumptions in more detail.

In order to be able to calculate the torques and forces acting on the selected drill string, the following assumptions have to be made. For calculations the drill string is assumed to be made up of short elements of 30 or 50 m in length. For each of these segments, the basic equations of friction are applied where it is possible to calculate tension, compression and torsion. The only required input data for this calculation procedure is the detailed BHA information as well as the survey and the mud weight. This principle starts at the bottom with the necessary boundary conditions WOB and bit torque. The parameters mentioned are then calculated for each segment from bottom to top, where finally cumulative values can be calculated for surface hook load and surface torque.

One limitation with the soft-string model is the missing bending moment in the calculation process. As it is assumed that the drill string is in continuous contact with the wellbore over the whole wellbore path, any bending moments as well as hole clearance effects are neglected.

## Stiff-String Model

In contrast to the soft-string models, the stiff-string models account for additional factors acting on a drill string situated in the wellbore. Besides the already-mentioned bending forces, they also consider radial clearance issues. This is done by not assuming that the string is in contact with the wall over the entire length of the wellbore. Several further factors are implemented in stiff-string models:

- Stiff tubular forced around curves results in higher side wall forces
- Variation in contact area between string components and the wellbore
- Presence of stabilizers, tool joints and casing centralizers

Including these parameters in T&D analysis should allow the drilling engineer to produce more realistic and valuable results. The mathematical model behind the stiff-string approach is much more complicated and complex to solve due to the greater amount of equations needed to include the additional parameters. Finite difference, finite element and semi-analytical techniques are commonly used to deal with the greater variety of numerical methods.

Generally, there are rules of thumb about whether to use a stiff- or a soft-string model for T&D calculations. The stiff-string approaches are designed to be used when dealing with following situations:

- Tortuous trajectories
- High dogleg severity
- Stiff tubular components in drill string
- Narrow radial clearances

Although one would expect more precise and better matching results with the stiff-string models, there is still a high amount of discrepancy between theory and practice. According to the literature and field tests, the stiff-string models fail under certain circumstances, especially when talking about hole size and radial clearance effects. The failure in properly accounting for these effects can lead the responsible engineers to wrong assumptions leading to problems in the planning phase.

The next figure shows the problem which occurs with the models that do not properly account for hole clearance effects. Generally, higher friction factors are examined when comparing casing running with drill pipe tripping in the same hole. This can be explained by the fact that due to the larger casing diameters the hole clearance is decreased accordingly.

The figure below shows hook load versus depth for several models conducted for a 9 5/8” casing that was run in a 12 ¼” hole. Each line represents a different radial clearance for the stiff-string model. In addition, the line for the soft-string model can be seen in light green color.

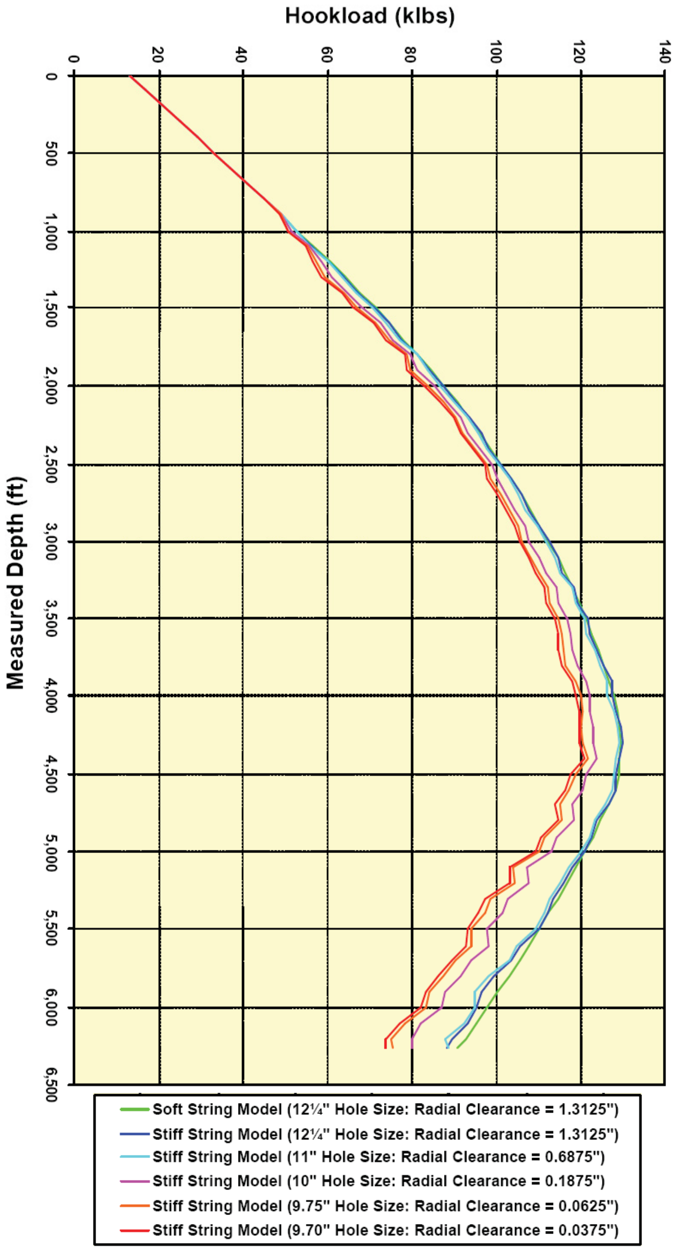


Figure 10: Comparison of stiff sting and soft-string model [5]

The reason for this comparison was to examine the effects on the stiff-string model when decreasing the hole size, and therefore the clearance. As one can clearly see, the stiff-string model with a radial clearance of only 0.0375” still shows a feasible trend in hook load, meaning that the casing can be run to total depth, although this could never be accomplished in reality.

Further investigations made in the field showed that severe doglegs in the top hole region, with a well path of already more than 30° inclination, lead to unrealistic results in the models.

When summarizing the limitations of the T&D modeling following list of factors must be conducted:

- Hole size, casing size, clearance
- Inclination
- Casing stiffness
- Tortuosity effects
- Resolution of survey data

All these facts have to be accounted for in reality. Therefore, it is necessary to understand that friction factors can not be easily re-used for different run types. For example a friction factor of a drilling run cannot be used for the subsequent casing that is run into the hole. In addition, the friction factors can not be interchanged between the described soft- and stiff-string models.

## Buckling

The term buckling was already mentioned several times throughout this thesis. This chapter will explain in more detail what the buckling phenomenon is and addresses the importance of considering buckling already in the T&D modeling phase.

Buckling is the term used whenever a failure mode needs to be characterized that occurs due to high comprehensive strength. In drilling engineering, buckling occurs when the drill string is subjected to high loads of compression that cannot be supported by the material anymore. This results in a structural failure of the tubular assembly. Following different buckling modes exist:

- Sinusoidal buckling
- Transition buckling
- Helical buckling

The most general mode, the sinusoidal buckling, occurs already when the string snakes along the wellbore. This causes an increase in contact force between the tubes and the wellbore. Any further compression can lead the buckled portion to transit into a helix. This mode is known as helical buckling.

Once a drill string is facing buckling of any type mentioned above, any further weight released from the hook is not supported by the bit anymore. This happens due to the increased contact area between the buckled part of the string and the formation. Instead of transferring the weight down to the bit to optimize ROP, the string is progressively supported by wellbore friction. Ultimately, this can cause the string to lock-up in the well, where no weight can be transferred down to the bit anymore as it is totally consumed by the buckled portion of the string. This may not only result in stopped drilling operations but also in a stuck pipe situation. If wellbore friction becomes too high, it is possible that the string cannot be run out of the hole anymore within the hook load limits of the rig.

Several models and calculations for buckling have been designed during the last centuries. The equations developed are well known to every drilling engineer who has to design a drill string for a new project. Generally, every engineer tries to design a scenario (survey, BHA, drill pipe) where buckling is completely avoided. Unfortunately, this cannot be achieved all the time as more and more difficult well paths have to be drilled. The increase in horizontal wells drilled in the last two centuries shows that due to bringing the material’s properties to its limits, it is not always possible to stay completely on the safe side. There is a general acceptance in drilling to tolerate sinusoidal buckling if there is no other possibility. In contrast to this, helical buckling should be avoided all the time. If even helical buckling is unavoidable, it is necessary to calculate the additional drag that will act on the post-buckled portion of the string.

Generally, the behavior of a drill string, acting beyond the limits of buckling, needs to be better understood. Of course failures will occur due to excessive local stresses in the post-buckled region. Loss of WOB and the high potential of cracks in the steel are technical issues that come up especially when going beyond the helical buckling limits. Due to the cyclic stress reversals, resulting from pipe rotation, the fatigue life is decreased dramatically.

As already stated, the awareness of buckling has to be included in T&D programs in a more graphical way. This can allow the driller and the engineers to react earlier, especially when using a program at the rig and in real-time. Drilling and completion engineers especially would get a good possibility to see under which circumstances and for how long a string can work in sinusoidal or helical buckling mode.

The buckling visualization method of ‘On-Line T&D’, described on page 15, seems to be a good possibility to assist the responsible field personnel and planning engineers. Nevertheless, there is a common problem with the models when trying to simulate casing runs in highly deviated wells. Due to the high loads, the casing is often floated to total depth. As a consequence the casing string is nearly weightless. The advantage of this situation is that frictional drag can be minimized. Unfortunately, most of the T&D models available indicate that the casing will helically buckle in such situations. As casing has a high stiffness, buckling resistance would be expected when floating the string into the hole.

## *Fluid Flow Effects*

Another area of interest in T&D modeling deals with the effects resulting from fluid flow. There are some models existing which correctly account for these effects but they are ignored by the majority.

Of course, fluid flow effects can only play a role during drilling and wellbore conditioning operations. While circulating mud through the string and the annulus, a loss of the normal component of the fluid pressure occurs due to the frictional contact between the fluid and the string. Furthermore, the shear stresses exerted by the fluid flow on the string have to be taken into account.

These two effects resulting from fluid flow only have to be considered for hook load calculations as there is nearly no effect on torque. Due to the circulation, the effective weight of the string can be reduced significantly. Depending on the wellbore construction elements, the BHA and the flow rate, the size of the so-called uplift is defined. Especially for coiled tubing and casing drilling operations this effect has to be considered.

As already stated, only a minor part of available T&D software takes fluid flow effects into account for model calculation. The absence of fluid flow effects while simulating a scenario with running pumps can lead to meaningless results. This is especially the case for operations in an 8 ½” hole.

The effects of fluid flow on torque and drag design clearly show that proper design and management goes hand in hand with hydraulics monitoring to assist the engineers and drillers during difficult drilling operations. As there is a great amount of rheological and fluid flow models available, they should be included in T&D programs.

## *Tortuosity*

The term tortuosity is used to describe the ‘crookedness’ of an as-drilled well profile. [6] It generally occurs when a wellbore deviates from a straight hole. There are two types of tortuosity known in the oilfield industry, among which the most common one is the local dogleg created when using a steerable motor. Due to the regular changes in drilling mode between rotary and sliding drilling, the occurrence of doglegs is very likely. The second type is often referred to as 'micro-tortuosity' which indicates a spiraled hole axis instead of a straight one. This is often associated with the use of short-gauge bits. Unfortunately, this type of tortuosity often results in poor hole quality and is a major contributor to today's friction factor problems. Field studies have shown that hole spiraling can be easily reduced by the use of extended-gauge bits and rotary steerable systems which decrease the 'Tortuosity Index' (T.I.) significantly.

The conventional dogleg is generally quite easy to detect by the use of survey data. In contrast to that, the recognition of hole spiraling is more difficult. The problem coming up with micro-tortuosity is that it cannot be detected by conventional 'Measurement While Drilling' (MWD) tools. It can only be seen from image and oriented caliper logs because with MWD tools, only the inclination and direction of the drift of the tool in the wellbore is measured and not that of the wellbore itself. An image of micro-tortuosity can be seen below.

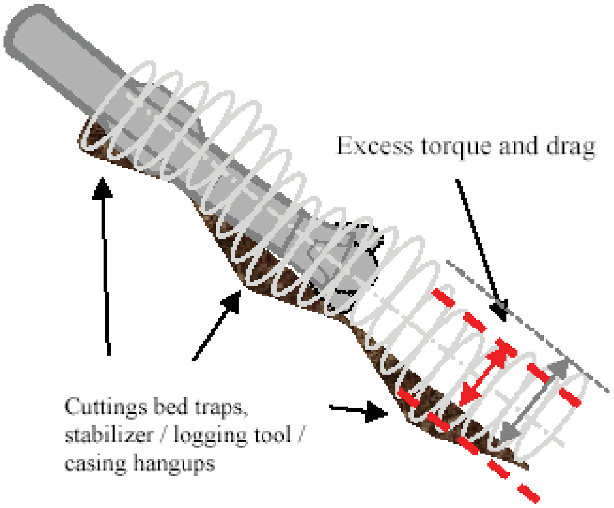


Figure 11: Hole spiraling or micro-tortuosity [7]

When using T&D software in the planning phase of a project, there is generally a tortuosity model applied to the smooth planned survey in order to make the planned well path to an as-drilled profile. In order to be as realistic as possible with the model, the Tortuosity Index (a kind of rippling effect) is added to a portion of the borehole. There is a common approach to ignore the tortuosity effects but to account for it indirectly by inflating the friction factors.

## Conclusion on T&D Model Limitations

As stated above, there are several parameters in T&D model design which need further improvement. Currently there are three main issues leading engineers to wrong results:

- Hole size and the resulting clearance does not affect results
- Friction factors for drilling operations are used for running casing design
- Differentiation and consideration of static friction effects

Generally it needs to be stated, that many engineers only use inflated friction factors in order to take all other ‘minor’ effects into account. According to the literature, there are many parameters available which affect T&D design but it has become a common practice to adjust for them by using correction factors. Most of these additional parameters are only a minor contributor in the overall results, so that they need not to be accounted for.

Nevertheless, there are some effects, as listed above, which may lead users to wrong assumptions and should therefore be included in more improved T&D software packages. An improved stiff-string model is one of the issues that would be required most.

# T&D Monitoring – A New Approach

Up to now, only already available T&D monitoring approaches have been described and compared with each other. Besides the evaluation of several existing techniques, the main purpose of this thesis was to develop a completely new real-time tool that is capable of tracking the two critical drilling parameters, namely torque and drag, in a highly improved way. Therefore, the study of existing systems was necessary in order to evaluate the state of the art in T&D monitoring prior to development.

The general objective of the system to be developed was to provide a real-time drilling monitoring solution that allows continuous evaluation of wellbore condition with critical parameters especially for the drilling of highly deviated and extended reach wells. This was the main goal to be achieved with the new tool. The following scope of work outlining the functionality and monitoring of critical parameters was defined in the very beginning:

- Wellbore Health Monitoring
    - Hook load and Torque Monitoring
    - FF Monitoring
    - Hole Cleaning Monitoring

There was no clear specification in the start-up phase about how the new application should visualize the results to the drilling personnel. The only stated objective was to develop the tool in a way that even inexperienced computer and software users can benefit from the provided results. Therefore, several iteration steps were necessary to actually find out which method will satisfy the costumers' wishes most, so that everybody can benefit from the use of the tool. The first workshops together with drilling engineers as well as the evaluation phase have shown that the T&D results should be provided in a way the engineers and field personnel are used to. The general feedback indicated a need to remain using the value over depth plots instead of developing completely new visualization methods. To present the results to the user in a familiar format turned out to be most appropriate.

A clear goal to achieve was to totally automate most of the tool's functions in a way that only a minimum of engineering intervention and assistance is required during the well construction process.

The implementation of the outlined system was split into several phases:

- Phase I, Definition Phase including the development start
- Phase II, Proof of Concept
- Phase III, Testing and Evaluation of the monitoring tool
- Phase IV, Implementation and Feedback

All phases, the development progress as well as the tool itself will be described throughout the following chapters. Prior to this description, the main purpose and concept of the new approach will be described in more detail.

## Wellbore Health Monitoring – Concept and Purpose

The basic idea behind monitoring wellbore health is to reduce lost and hidden lost time during drilling operations. In the context of this project, these two flat time sources often resulting from bad hole conditions and/or improper operational procedure, are to be reduced. Especially today's increase in the drilling of highly inclined and extended reach wells often results in increased reaming and washing time. The amount of and correct way to perform wellbore conditioning, including reaming up/down, washing up/down and circulation operations, is often totally left to the driller at the break. It is not yet a common and standardized approach to evaluate how much wellbore conditioning is actually necessary to achieve a proper hole condition. Tools assisting in analysis of the condition of a borehole are approaching, but they are infrequently used as most of them are simply too difficult to use and very sophisticated. Of course, highly advanced features and special applications need to be available for performance and planning engineers, but there are often too many add-ons included that would complicate things for the field personnel if they would have to use these tools too. As a consequence, there should also be tools available that effectively help the personnel at the rig site actually drilling the hole. For example, when they can be made aware that there is a potential to save time by reaming only half as much as they had been doing in order to avoid getting stuck or encountering other troubles, this can prove to be a useful way of reducing unnecessary wellbore conditioning time which positively affects the operator's goal of operational efficiency. Unfortunately, this is not yet the case and therefore the driller will always rely on his old proven methods without reducing the amount of wellbore conditioning just to be faster.

As there is commonly a 'stick to the old reliable methods' way of thinking at the rig site, important parameters are preferably taken manually instead of trusting automated systems to define best practices for performance improvement. Therefore, a change in the philosophy needs to be made on how to present results from automated systems to the crew at the rig. It is very important, once real-time systems are used, to adjust the workflow and the system in a way that both drilling teams, the one at the rig site and the other one in the remote operating center, collaborate to manage the challenges coming up with difficult wells. It is very important to establish a 'no blame' environment with continuous training and optimization.

One problem is that important drilling parameters are still recorded manually most of the time. [8] This is especially the case for hook load while moving and torque while rotating a tubular assembly. By analysis of these two parameters in real-time, which are of most concern when drilling inclined and horizontal wells, a huge potential in reducing lost as well as hidden lost time can be achieved. Nevertheless, this can only be accomplished with the rigorous use of real-time sensor data measured at the rig site. The common method of measuring dozens of channels but not using them for further analysis needs to be changed. One advancing method is the totally automatic operations recognition which can be run on the real-time sensor data. This automated process allows continuous identification of the current rig operations (drilling mode, type of wellbore conditioning, etc.) without any human intervention.

By using the automated system based on real-time drilling data, it is possible to reduce lost and hidden lost time. How this is achieved can be easily explained by the following example. As the operations recognition allows continuous identification of the rigs' status and ongoing operations, it is possible to get pick up, slack off and rotating weights as well as torque values during tripping, reaming and drilling. The detection and automatic identification of these relevant parameters allows real-time analysis without interfering with the drilling operations or requiring extra time or work force. Furthermore, when comparing actual torque and hook load values with simulated (planned) ones, one can easily identify if further wellbore conditioning is necessary or if it can be avoided. This means that excessive reaming and washing can be eliminated if the visualized results show that there is already low torque and drag which may be an indication for a good hole quality. As a consequence, the unnecessary practice of reaming more to be on the safe side can be corrected and hidden lost time can be saved. In addition, lost time can be avoided as instant measures against increasing torque and drag can be taken before critical ranges are succeeded. The necessary counteractions can be conducted immediately, as there is no need to manually process the hand taken values to get a graphical illustration of T&D results.

A more detailed description of the automated operations detection based on real-time sensor data can be found in the chapter 'Automated Operations Recognition'.

Some of the main expected benefits from monitoring wellbore health are listed below:

- Possibility to optimize flat times
    - Utilize wellbore conditioning efforts in the best possible way

    - Define best practice
    - Excessive reaming can be avoided
    - Immediate counteractions can be taken once a trend towards critical ranges is observed
- Quick method to evaluate hole condition and degradation thereof
- Possibility to determine reasons for increased friction
- Root cause identification and evaluation of responsive actions

As already stated, the functionality of the tool to be developed had to be based on real-time operations detection with a highly automated handling of the data, but also to be very user-friendly with a minimum in human intervention necessary. A very detailed description of the development steps and the functions can be found throughout the next chapters.

# Phase I – Definition Phase

This chapter describes all the definitions and specifications of the tool to be developed, as well as the start of development. Furthermore, the feasibility of the approach to monitor wellbore condition in real-time had to be proved. It was necessary to work through several ideas of how the new real-time drilling monitoring approach should look like and in which way the results should be visualized to the field personnel at the rig and to the drilling engineers in the office. Several different possibilities have been worked out and proved for their applicability in real-time mode.

Generally it needs to be stated, that due to the evaluation study done in advance, several possibilities and ideas of how to graphically present T&D results were available. Nevertheless, it was necessary to start at the very beginning, as many problems arose with the special T&D operations detection which was an absolute requirement for real-time visualization.

The possibility of having a plot showing continuous values of hook load and/or torque over depth/time as shown below was not an option. A clear differentiation algorithm for RIH, POOH and ROB while drilling, tripping and wellbore conditioning for individual BHA runs, had to be developed. As Figure 12 indicates, the continuous plotting of values over time can get quite confusing due to a missing operations algorithm. In this example only the real-time measured values are shown, with one simulated (planned) curve.

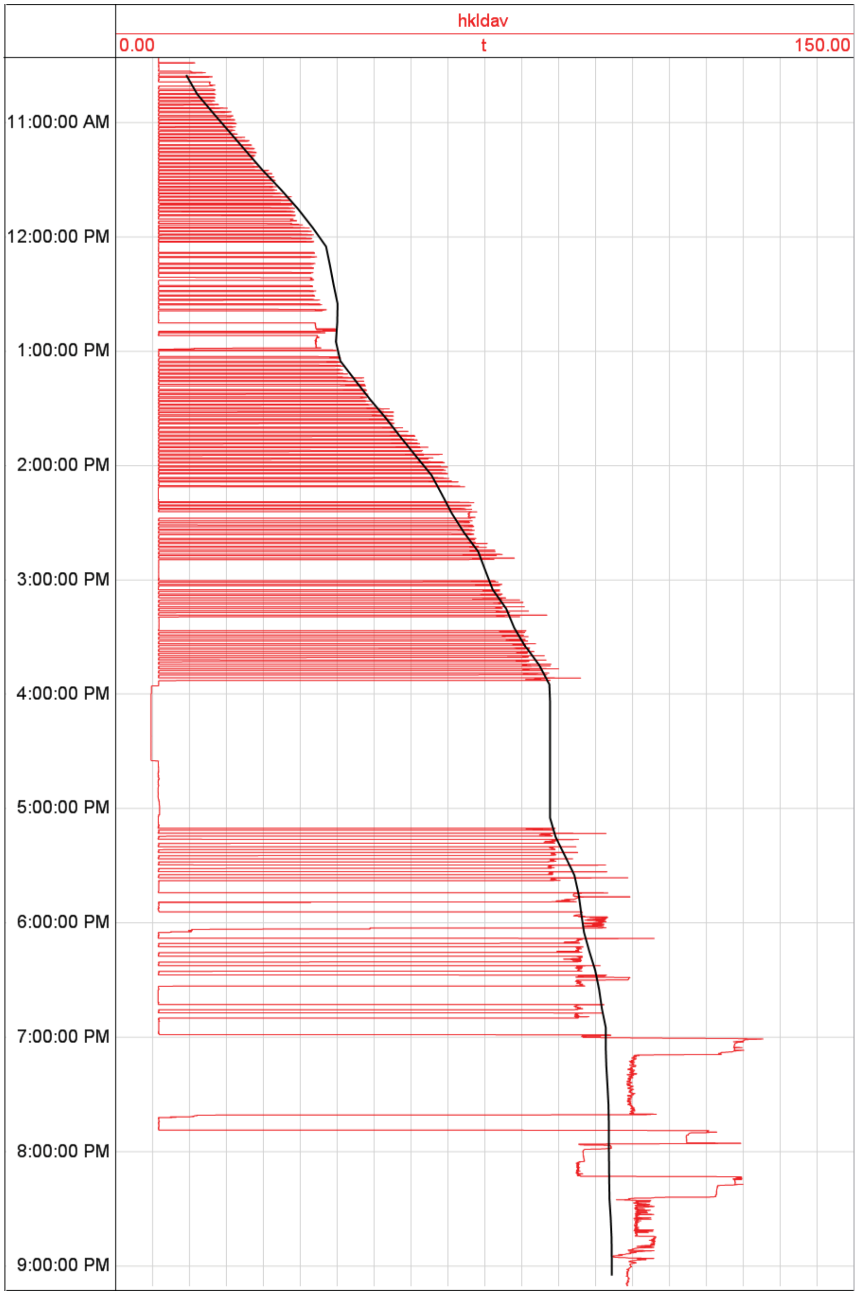


Figure 12: Simple plot of measured hook load versus time with one simulated curve

During the first workshops with drilling engineers as well as drilling supervisors, several different plots of interest have been defined:

- Tension Comparison / Tension Profile including following curves:
    - ‘Running In Hole’ (RIH) with a family of WOB / FF curves (Figure 13)
    - ‘Rotating Off Bottom’ (ROB)

    - ‘Pulling Out Of Hole’ (POOH) for a family of FF curves (Figure 14)
    - Critical buckling curves (Figure 13)
- Torque Profile:
    - For a family of FF curves (Figure 15)
    - Maximum allowable torque line (make-up torque of weakest connection)
- Hook load (hkld) and torque (tq) over depth (Figures 16 and 17):
    - For a family of FF curves
    - Hysteresis (Figure 18)
- Delta hook load (∆hkld) plot (‘Wellbore Aging’) (Figure 19)
- FF over depth

For all of the possible plots listed above an example is shown throughout the next several pages. Figures 13 to 16 show planned curves of the relevant parameters, namely hook load and torque, during the operations RIH, POOH and ROB.

It was not in the scope of this project to program a new simulator to develop torque and drag models that are most realistic and exact. The focus was on giving the user clear information about the trend of the actual hook load and torque compared to planned values. This can simply be done by overlaying the expected curves with the real-time values based on sensor data and an operations recognition algorithm. A proper illustration method can then allow the user to compare actual versus planned hook load, torque respectively and to focus on the trend development. Based on a trend analysis, conclusions on the wellbore health status can be made.

An example for such an actual versus planned trend comparison can be found in Figure 17.

In order to avoid a continuous plot of values versus depth or time as shown before, it was necessary to use an operations detection algorithm to be able to focus only on the three T&D relevant operations (RIH, POOH, ROB). How this was achieved and implemented will be described in more detail during the next two chapters.

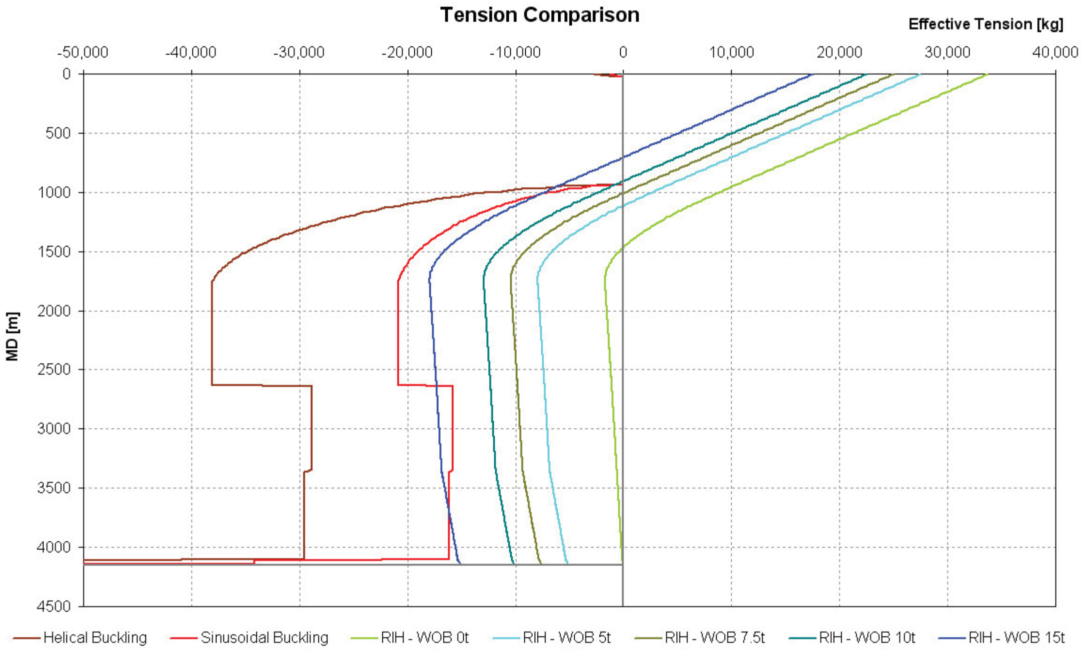


Figure 13: Tension comparison – RIH for 5 different WOB curves and buckling limits

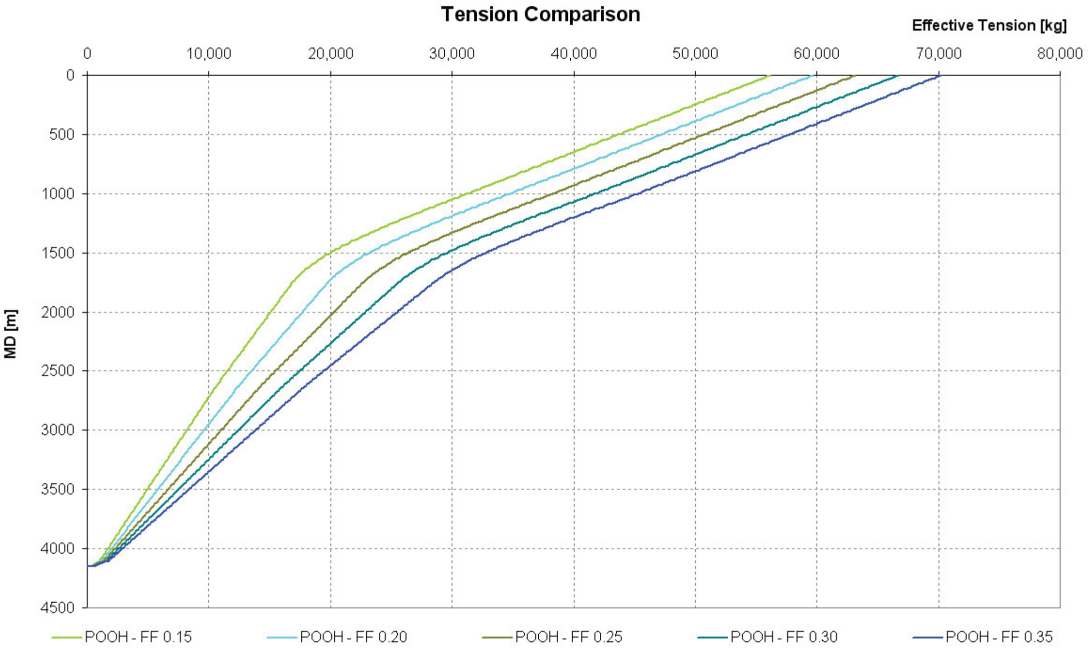


Figure 14: Tension comparison: POOH for a family of FF curves

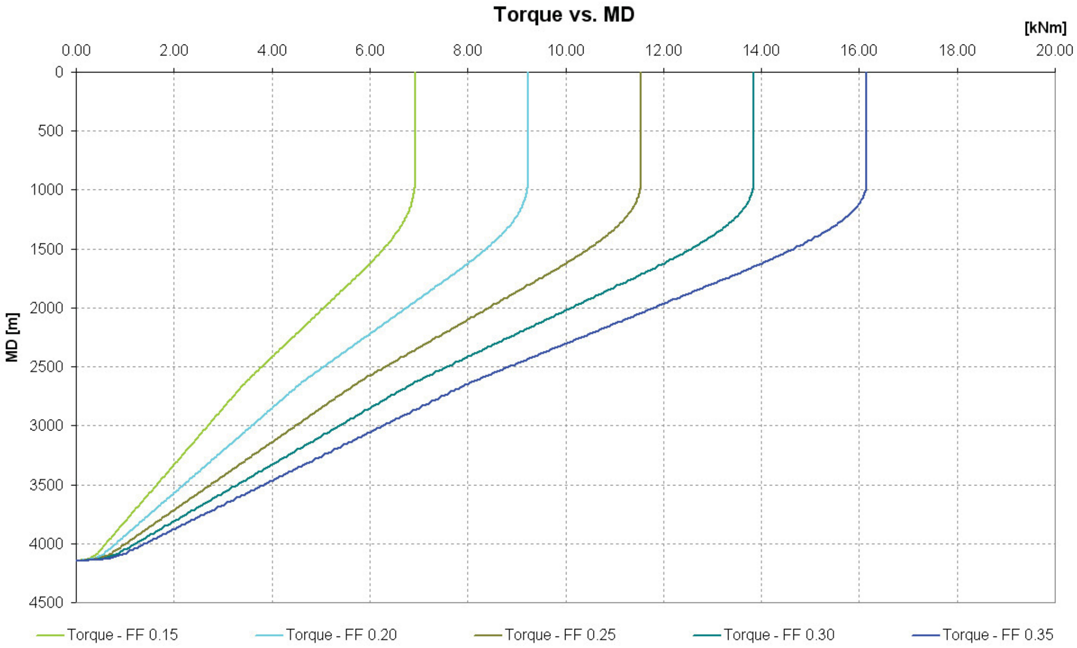


Figure 15: Torque profile for a family of FF curves

The figure below differs from the three previous ones as it shows the surface hook load over depth. The method used for the previous plots is an incremental approach where the hook load (respectively torque) is calculated from bottom to top in incremental steps of 30 meters.

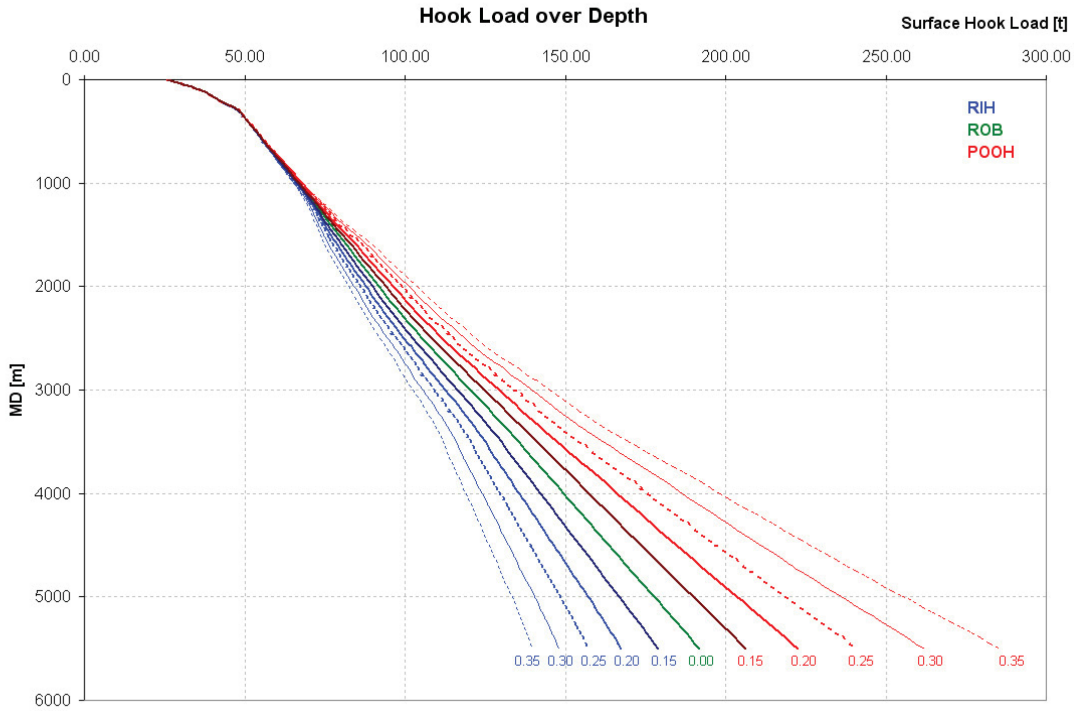


Figure 16: Hook load over depth

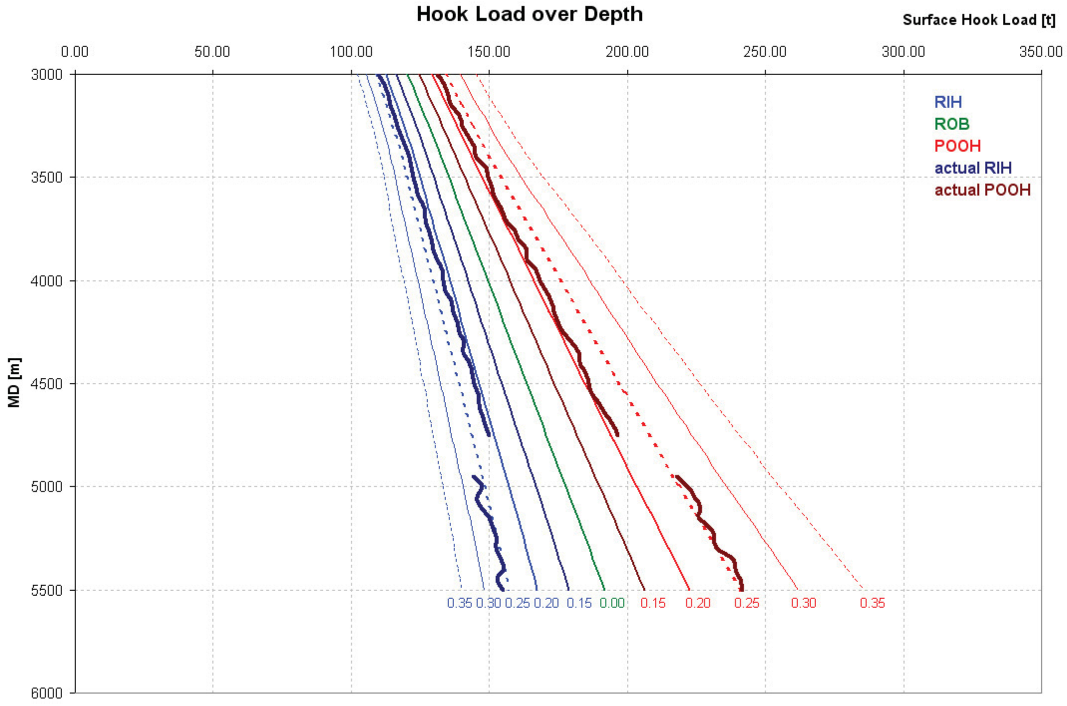


Figure 17: Simulated and actual hook load over depth

For the next two examples, the ‘Hysteresis’ and the ‘Wellbore Aging’ plots, only hand-drawings of possible real-time curves are shown.

The next plot again shows curves for the actual hook load over a certain depth interval. In this case a hysteresis without any simulated friction factor curves is used to present the results. Again, only the operations RIH, ROB and POOH for one certain BHA run are used. In contrast to the hook load over depth plots shown before, the sequence of the operations in time is considered. As it can be seen on the figure below, the plot starts with the RIH line, continues with the ROB and finishes with the operation POOH.

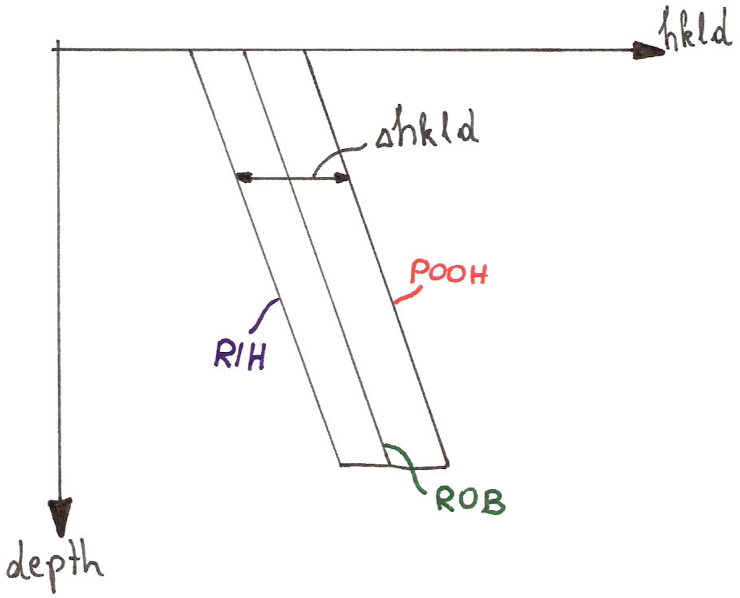


Figure 18: Hysteresis of hook load over depth

A delta hook load over depth plot (or Δhkld plot), as shown below, was discussed as a possibility to get a clear indication about the wellbore health status over time. It allows focusing on the condition of particular open hole sections. Formations causing troubles can then be tracked in more detail and open hole times can be optimized.

As the next figures indicate, the delta of the actual hook load values is plotted over depth. In order to be able to track the condition of the open hole, the time dimension was added to the X-axis. Discrepancies from the zero base line, highlighted with different colors, will allow the user to get an indication about hole sections that need more concern.

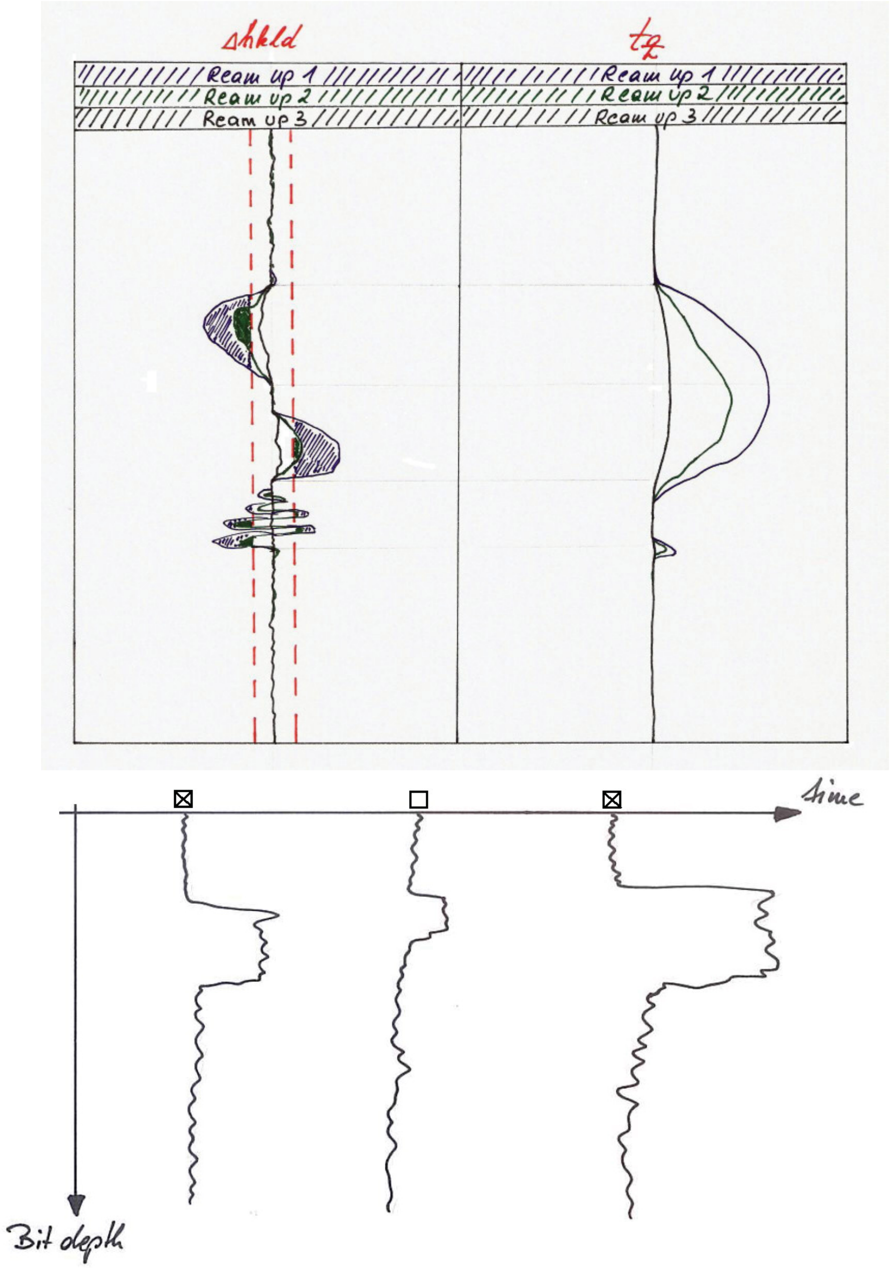


Figure 19: ‘Wellbore Aging’ plots

All of the plots discussed up to now have a good potential in assisting the engineers and field personnel in monitoring T&D in real-time. Nevertheless, the system to be developed was intended to give clear and easy information about the condition of the wellbore during the drilling operation, expressed in hook load and torque. In particular, drillers and drilling supervisors could then directly relate the results to the sensor information they visually get from their data provider’s screens. The whole package together, monitoring of T&D and the real-time sensor data over time, could then be used to react with proper counteractions as early as possible.

As a consequence, the approach of monitoring trends in hook load and torque seemed to be the most appropriate one for both operating teams. In contrast to all the other methods, the surface hook load and torque over depth plots, combining actual and planned values, met the highest approval among the engineers and field personnel. In comparison to the other approaches, this one has two major advantages:

- Less real-time simulation efforts required
- Approach does not lead to signatures that are much more complex to translate into actions especially for the driller at the break (e.g. FF over depth)

## *Automated Operations Recognition*

As already addressed, the method of choice was to visualize the data in value over depth plots for trend monitoring. By getting all the real-time data from the rig in a 1 Hz frequency, it would be very easy to plot the entire values over depth in the raw one second data. As shown in Figure 12 this can result in a very confusing plot.

As a consequence, it was necessary to find a solution to this problem as trend analysis would not really be possible with such a plot. In order to get a clearer picture to see emerging trends, the amount of data points in the plot had to be reduced. The decision was made that each stand of pipe had to be represented by one data point instead of thousands of values. The detection of such stands out of the real-time data was one of the greatest challenges in the whole project as it had to be completely automatic and very smart. In addition, the particular T&D related operations RIH, ROB, and POOH had to be detected automatically without any human intervention.

The next paragraphs describe the principle of the automated operations recognition (OpRec) used for the T&D monitoring approach.

The OpRec is a rule-based system that has been developed for autonomous analysis of real-time surface sensor data measured by the various data providers at the rig-site. The system allows evaluation of the sensor data and acquires crucial process information as a basis for further analysis [9, 10]. The common procedure to analyze drilling operations is still based on conventional activity breakdowns that are reported in daily morning reports. As these reports are reflecting human observations and judgment, the accuracy of the results is quite limited. In addition, the coarse level of detail (only operations with 15 to 30 minutes are reported) together with subjective coding systems limit any analysis on drilling performance.

Due to all these limitations, the need of a system capable of recognizing drilling operations such as tripping, making connections, reaming, washing, drilling mode etc. became more and more obvious. Therefore, the operations recognition was developed as a system to extend and enhance standard reporting for further analysis.

As already stated, the automated OpRec is based on logical rules applied to several real-time data channels. For each operation to recognize (e.g. drilling) a set of rules has to be defined. Each rule depends of a condition part and a conclusion part and can consist of several other rules in addition to the sensor data channels. This means that based on several data channels, their values and their interaction, the type of operation is definite. As an example the WITS channels ‘Bit Depth (meas)’, ‘Hole Depth (meas)’, ‘Surface RPM‘ and ‘Flow In Pump‘ are necessary for detecting rotary and sliding drilling. All of these channels need to be available to get a maximum of information about the drilling mode. Of course the ‘Hole Depth’ channel alone would be sufficient enough to detect if there is hole made or not, but only the combination of all of the listed channels allows differentiation between drilling modes and wellbore conditioning while drilling.

Beside the availability of certain necessary channels, data quality as well as data frequency play a very big role in the automated operations detection. For the analysis based on real-time data a frequency of 1 Hz is recommended with an upper limit of 0.2 Hz. With 10 seconds data the recognition accuracy for certain operations starts to decrease significantly. With data updated in intervals of 30 seconds, which is still standard for several mud logging companies, several operations can not be detected at all (e.g. fast slip to slip connections, pipe spinning times etc.). Data quality is crucial to be on a very high level for any type of analysis based on sensor data. Misaligned hook load sensors, bad depth tracking and wrong thresholds for calculated channels are only three issues that have to be addressed very frequently. In order to avoid any of these issues to influence analysis results, an automatic and manual quality control check is performed including following steps: [11]

- Data Range Check
- Gap Filling
- Outlier Removal
- Noise Reduction
- Logical Checks

Especially the use of different filters (mean, median, conservative smoothing and wavelet decomposition) to remove outliers from the dataset is of high importance when working with a large amount of sensor data.

### T&D OpRec Rules

As already stated, it was necessary to develop several new rules for the automatic detection of T&D related operations. The following basic states had to be detected for the plot prototype:

- RIH, ROB and POOH (T&D operations) on a stand by stand basis (considering difference between drilling, tripping and running casing/liner/tubing) → 'TaD_Rule'
- Stands of tubular assembly moved up or down in the hole
- Hook load and torque during T&D operations
- One filtered value of torque and hook load representing a stand of pipe (including the corresponding stand depth) → 'HxD' and 'TaD_Rule'

In order to be able to test the newly developed rules, a dataset of an 18° inclined 3000m well was used. All screenshots below showing real-time data are referring to this well, named 'Testwell' throughout the thesis.

First step in designing rules, beside the selection of an appropriate dataset for testing, is the design of a decision tree. As such rules are based on logical statements and interactions between data channels; a decision tree as shown below is a very good approach in starting the iteration process.

The intention of the 'TaD_Rule' was to detect following states: RIH, POOH, and ROB. During these operations the bit is off always off bottom. As no points while actually making hole had to be plotted, the first decision in the rule was set to be if the bit is on bottom or not. From there on, several other channels and logical decisions were implemented to find out if one of the T&D operations is active or not. A list of these decisions as well as the necessary sensor channels can be found below the decision tree.

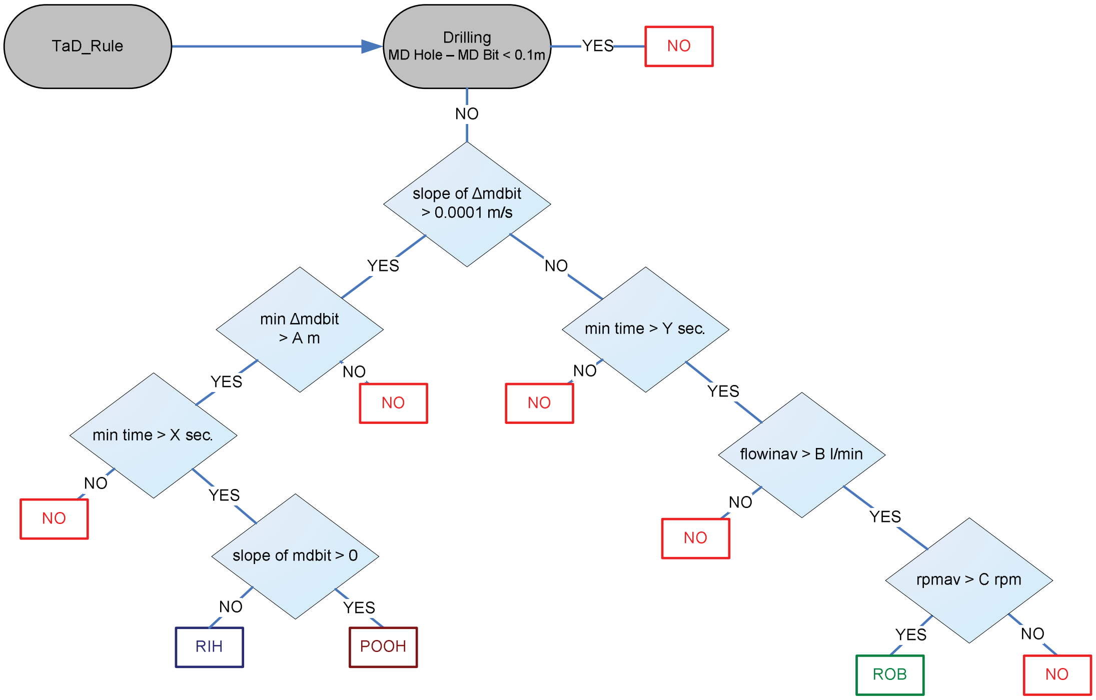


Figure 20: First decision tree for plot prototype

Based on the decision that the bit is off bottom, the following paths in the tree with additional parameters (thresholds) are possible:

- Path with string movement (RIH or POOH) – left path
    - Thresholds for:
        - Velocity of string movement
        - Minimum traveling distance of the string
        - Minimum time of string movement
    - ‘Bit Depth’ (mdbit) slope for differentiation between RIH (negative) and POOH (positive).
- Path without string movement (ROB) – right path
    - Thresholds for:
        - Velocity of string movement
        - Minimum time for a ROB operation
        - Minimum flow rate through the pipe
        - Minimum surface revolutions of the pipe

Following real-time data channels are necessary for the 'TaD_Rule':

- Hole Depth (meas) (mdhole)
- Bit Depth (meas) (mdbit)
- Surface RPM (rpmav)
- Flow In Pump (flowinav)
- Block Position (posblock)
- Surface Hook Load (hkldav)
- Optional backup channels:
    - Bit Rotation (bitrpm)
    - Total Pump Pressure (prespumpav)

Once all the logical decisions are finished, one of the states RIH, POOH, ROB, NO or UNKN must exist for the 'TaD_Rule'. In the case of missing channels or bad data (flagged with the WITS NULL value '-999.25'), the rule will automatically jump into the unknown (UNKN) state.

The next step was to test this rule in very detail with the use of the 'Testwell' dataset. The operations recognition algorithm was run over the data in historic mode. This was followed by analysis of the exactness of the results as the thresholds and parameters had to be fine-tuned. In addition, appropriate buffer sizes and delays for channels and other rules had to be found. As OpRec rules are based on the interactions between rules and channels, exact availability times are crucial (e.g. 'TaD_Rule' can start once the rule 'Rotate', which decides if the drill string is rotated or not, is finished; due to this delay the 'Rotate' rule needs to be buffered in the system so that it is available when the 'TaD_Rule' needs it for deciding if ROB is active or not).

During this testing phase, appropriate defaults for the variable parameters had to be found. Generally, all of them can be adjusted, but the standards listed below seem to be the most appropriate ones based on the dataset used.

- Slope in bit depth to separate ROB from RIH and POOH: 0.0001 m/s
- Min Δmdbit (A m): 3 meters (minimum delta in 'Bit Depth' to activate rule)
- Min time (X sec): 10 seconds (minimum time POOH or RIH has to last)
- Min time (Y sec): 20 seconds (minimum time ROB has to last)
- Min flowinav (B l/min): 30 l/min
- Min rpmav (C rpm): 10 rpm

For the stand detection a user-definable trigger was included which is the ’min Δmdbit’. This parameter defines the depth difference in bit depth the string has to travel in order to trigger the calculation of one median value. If it seems useful to trigger the calculation not after the traveling of the entire stand, but also if the string has only traveled 5 meters (about 15 ft), this parameter can easily be adjusted.

As one can see from the values above, a data frequency of 1 Hz is highly recommended for the T&D operations detection. As this rule depends on actions very short in time, data update intervals of more than 3 to 4 seconds already highly decrease the accuracy of the results.

The next step was to develop the two rules calculating the hook load and torque values for each detected stand with their corresponding bit depth (‘HxD’ rule). Based on the successful detection of a stand (RIH, POOH or ROB), hook load and torque respectively are calculated by using a median filter as default. It is optional to use the mean filter instead of the median. For the corresponding depth, always the middle of a stand is used as reference value.

In addition to the use of a median filter for outlier elimination, a trimming value had to be included. This value was implemented to assure that acceleration forces in the beginning and in the end of a moved stand do not affect the calculated values. Basically it represents the time in seconds (7 seconds as default) for which all hook load and torque values are skipped at the beginning and in the end of a stand for the filter calculation.

Once all these parameters and thresholds had been optimized, the next step was to specify and develop the interface of the torque and drag visualization software (TaD tool). This will be described throughout the next chapter.

## Phase II - Proof of Concept

The second phase of the project was split into the following two parts:

- Specifications of the required features for prototype development
- Field test of T&D rules and prototype in real-time mode

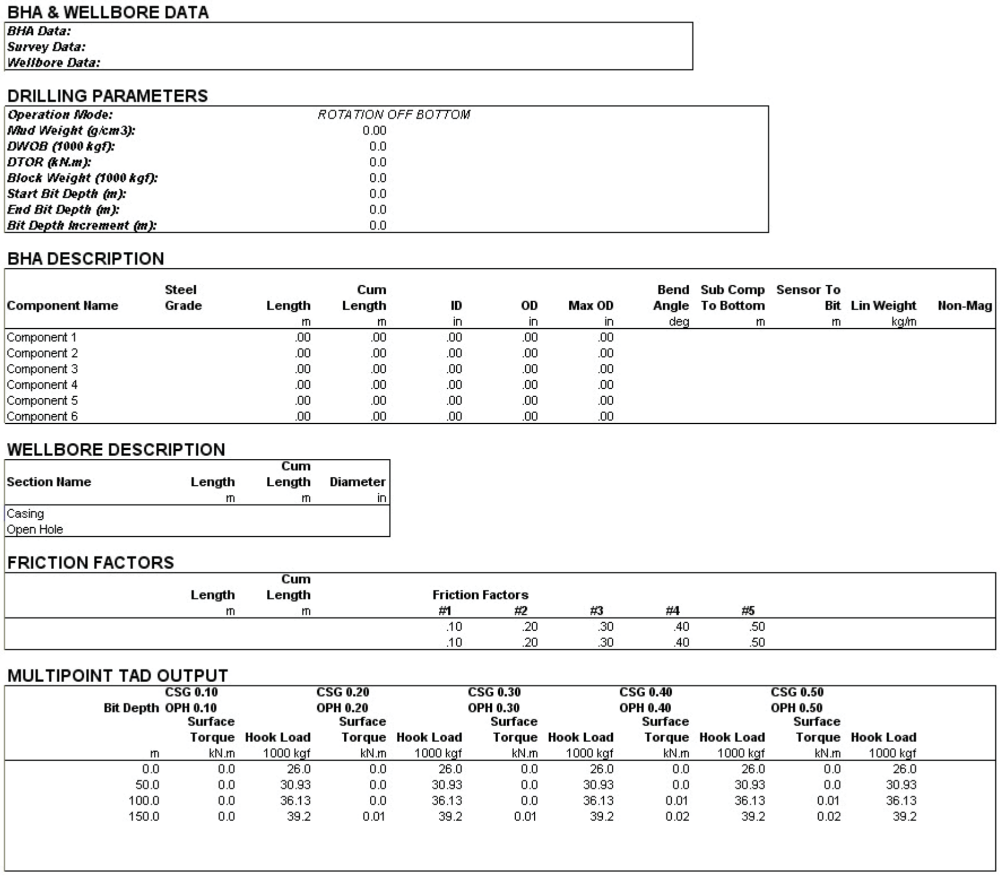
Both phases were run in parallel as the real-time field test allowed continuous testing of every new feature added to the prototype.

As stated above, the decision was made to focus on the surface hook load and torque over depth analyses. The specified plot type described in the previous chapter is based on the concept of plotting actual values for hook load and torque over different friction factor curves.

## Simulations, Improved 'TaD_Rule'

It is necessary to model the simulated curves for the operations RIH, POOH and ROB with a torque and drag simulation software. The output of this software needs to be three separate reports in Excel format containing tables of measured depth, hook load and torque for five different friction factors. First step was to define a standard structure for these reports to allow development of a 'Simulations Loader'. As there were several different exports delivered in the beginning, a standard had to be set for each model to assure that the data can be imported into the tool's database.

This standard export with the defined data structure for the three Excel files is shown below:



**BHA & WELLBORE DATA**

***BHA Data:***
***Survey Data:***
***Wellbore Data:***

**DRILLING PARAMETERS**

| | |
|---|---|
| ***Operation Mode:*** | *ROTATION OFF BOTTOM* |
| ***Mud Weight (g/cm3):*** | 0.00 |
| ***DWOB (1000 kgf):*** | 0.0 |
| ***DTOR (kN.m):*** | 0.0 |
| ***Block Weight (1000 kgf):*** | 0.0 |
| ***Start Bit Depth (m):*** | 0.0 |
| ***End Bit Depth (m):*** | 0.0 |
| ***Bit Depth Increment (m):*** | 0.0 |

**BHA DESCRIPTION**

| **Component Name** | **Steel Grade** | **Length** m | **Cum Length** m | **ID** in | **OD** in | **Max OD** in | **Bend Angle** deg | **Sub Comp To Bottom** m | **Sensor To Bit** m | **Lin Weight** kg/m | **Non-Mag** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Component 1 | | .00 | .00 | .00 | .00 | .00 | | | | | |
| Component 2 | | .00 | .00 | .00 | .00 | .00 | | | | | |
| Component 3 | | .00 | .00 | .00 | .00 | .00 | | | | | |
| Component 4 | | .00 | .00 | .00 | .00 | .00 | | | | | |
| Component 5 | | .00 | .00 | .00 | .00 | .00 | | | | | |
| Component 6 | | .00 | .00 | .00 | .00 | .00 | | | | | |

**WELLBORE DESCRIPTION**

| **Section Name** | **Length** m | **Cum Length** m | **Diameter** in |
|---|---|---|---|
| Casing | | | |
| Open Hole | | | |

**FRICTION FACTORS**

| | **Length** | **Cum Length** | **Friction Factors** | | | | |
|---|---|---|---|---|---|---|---|
| | m | m | **#1** | **#2** | **#3** | **#4** | **#5** |
| | | | .10 | .20 | .30 | .40 | .50 |
| | | | .10 | .20 | .30 | .40 | .50 |

**MULTIPOINT TAD OUTPUT**

| **Bit Depth** | **CSG 0.10**<br>**OPH 0.10** | | **CSG 0.20**<br>**OPH 0.20** | | **CSG 0.30**<br>**OPH 0.30** | | **CSG 0.40**<br>**OPH 0.40** | | **CSG 0.50**<br>**OPH 0.50** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Surface Torque** | **Hook Load** | **Surface Torque** | **Hook Load** | **Surface Torque** | **Hook Load** | **Surface Torque** | **Hook Load** | **Surface Torque** | **Hook Load** |
| m | kN.m | 1000 kgf | kN.m | 1000 kgf | kN.m | 1000 kgf | kN.m | 1000 kgf | kN.m | 1000 kgf |
| 0.0 | 0.0 | 26.0 | 0.0 | 26.0 | 0.0 | 26.0 | 0.0 | 26.0 | 0.0 | 26.0 |
| 50.0 | 0.0 | 30.93 | 0.0 | 30.93 | 0.0 | 30.93 | 0.0 | 30.93 | 0.0 | 30.93 |
| 100.0 | 0.0 | 36.13 | 0.0 | 36.13 | 0.0 | 36.13 | 0.01 | 36.13 | 0.01 | 36.13 |
| 150.0 | 0.0 | 39.2 | 0.01 | 39.2 | 0.01 | 39.2 | 0.02 | 39.2 | 0.02 | 39.2 |

Figure 21: Standard simulation model structure

It is important to mention, that one model consists of three Excel files and is only valid for one certain BHA, mud weight and wellbore geometry. There is no limit in the amount of models that can be loaded into the system.

The graphical output of the data exported was set to be the following:

- RIH: blue (lighter with increasing FF)
- POOH: red (lighter with increasing FF)
- ROB: green (bold line to indicate centre)

The next figure shows such simulated curves which have been plotted based on an export for the 'Testwell'.

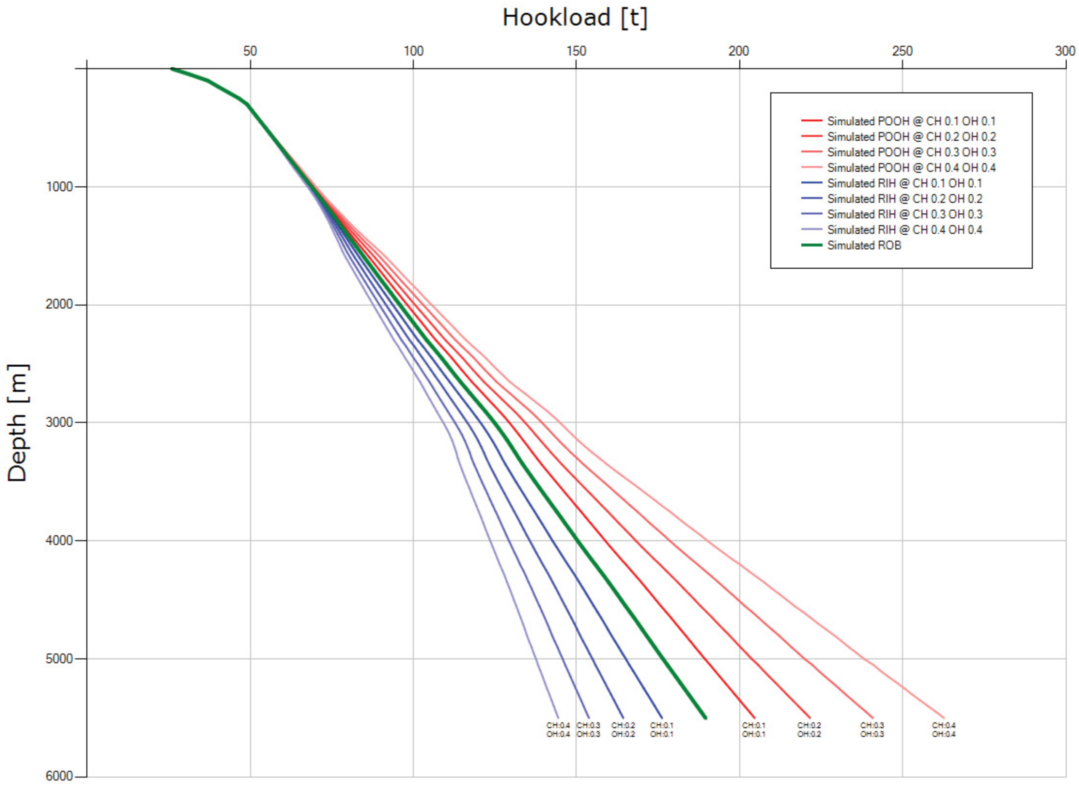


Figure 22: Graphical output of simulated curves based on Excel export

Once the simulations loader was implemented, the first RIH, POOH and ROB were plotted over the planned friction factor curves.

During the first tests of the rule and the visualization method, it was immediately obvious that the detection of real 'Slack Off' and 'Pick Up' weights during drilling operations is not that easy. As a stand of pipe is drilled down it is an uncommon operation to move this stand up and down afterwards without any rotation. Therefore, it was not always possible to detect the specified operations as they were simply not conducted. Generally the string is moved with rotation after a stand was drilled down. In order to avoid a time-consuming test (e.g.: ‘PRS Test’) to get T&D values, the decision was made to include these operations with rotation as a separate state in the ‘TaD_Rule’ for subsequent visualization. There was no intention to introduce a new standard rig operation after each drilled stand just to get real values for RIH and POOH. Due to the higher drag during such operations, stuck pipe situations could be the consequence.

For tripping operations this problem did not occur in the very beginning as the stands were typically moved without rotation. As it is also possible to ream in or out of the hole, this type of operation had to be implemented in the ‘TaD_Rule’ as well. The list below gives an overview on all the operations that can be visualized in the final version of the TaD prototype. Furthermore, the adopted decision tree for the ‘TaD_Rule’ can be seen in the next figure.

- POOH - ‘Pulling Out Of Hole’ while drilling [a]
- POOH Rotate - ‘Pulling Out Of Hole’ with rotation while drilling
- RIH - ‘Running In Hole’ while drilling
- RIH Rotate - ‘Running In Hole’ with rotation while drilling
- POOH Trip - ‘Pulling Out Of Hole’ while tripping [b]
- POOH Trip Rotate - ‘Pulling Out Of Hole’ with rotation while tripping
- RIH Trip - ‘Running In Hole’ while tripping
- RIH Trip Rotate - ‘Running In Hole’ with rotation while tripping
- ROB - ‘Rotating Off Bottom’ while drilling
- ROB Trip - ‘Rotating Off Bottom’ while tripping

---

[a] Distance of mdhole and mdbit is closer than a certain threshold (default 35 meters)
[b] Distance of mdhole and mdbit is larger than a certain threshold (default 35 meters)

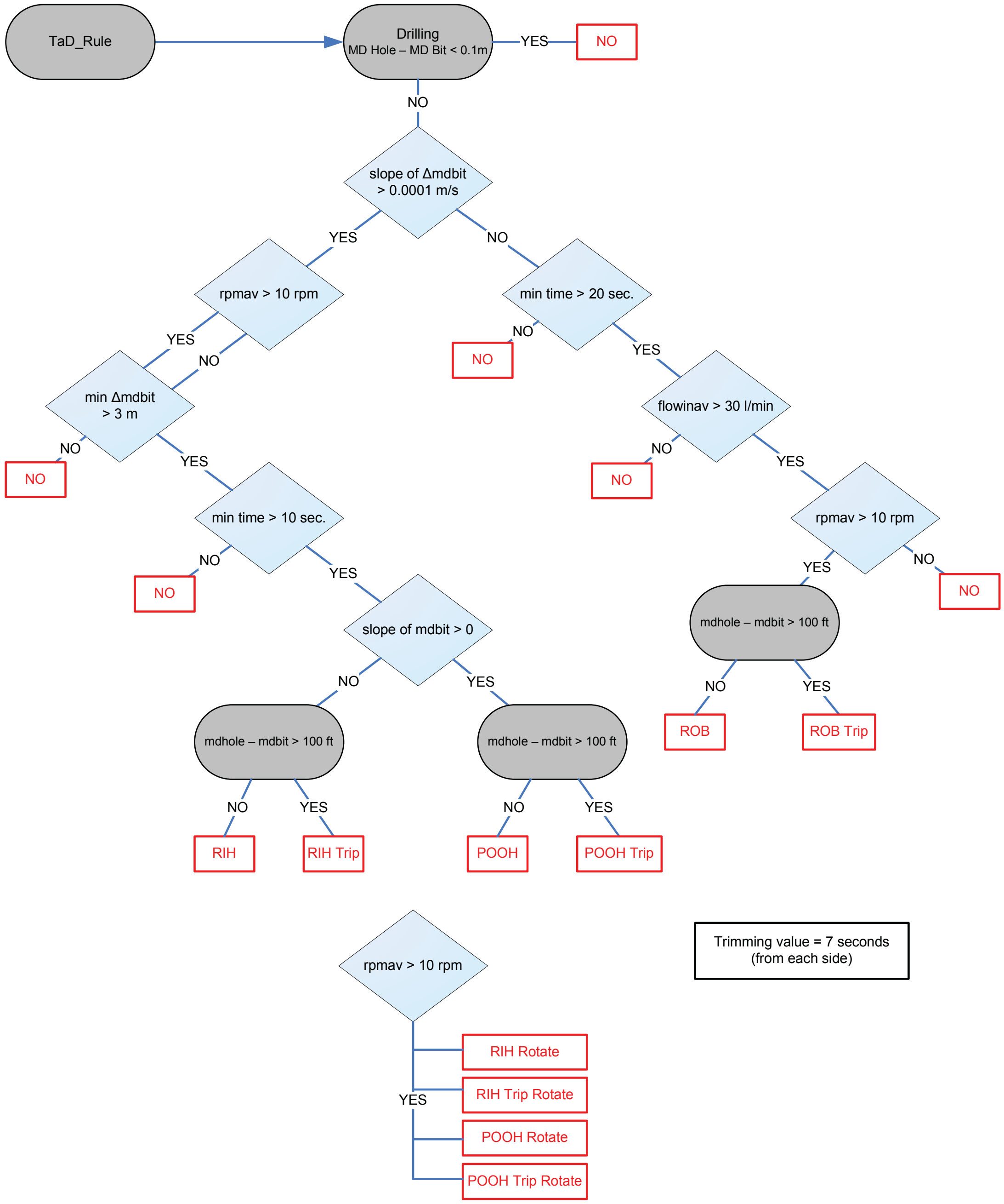


Figure 23: Final decision tree for the 'TaD_Rule'

In addition to the standard median (or mean) calculation for the operations listed above, the minimum value for RIH and the maximum value for POOH are calculated by default and can be displayed in the TaD tool.

Finally, also the out of slip (OOS) hook loads were of great interest. For this operation the hook load after each slip to slip connection is measured for an interval of 20 seconds. From these values, the maximum is used for visualization over depth in the

TaD tool. The figure below shows real-time data for a slip-to-connection (dark grey) and the subsequent OOS state (light red).

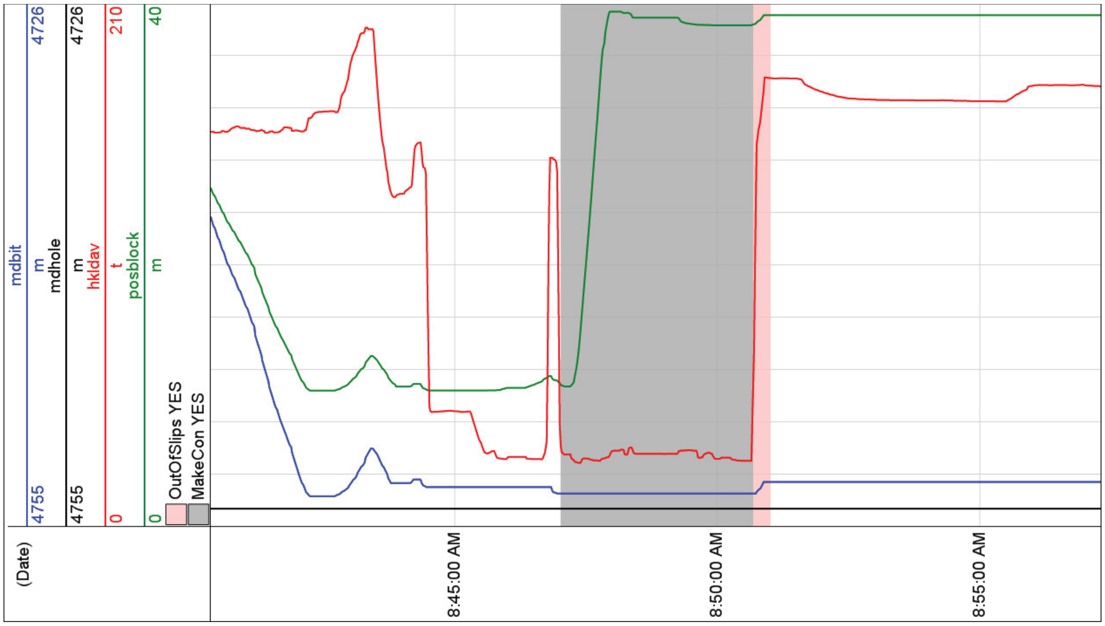


Figure 24: Real-time plot of several data channels showing OOS state

A list with all possible operations for visualization in the TaD tool can be found in the chapter below. Furthermore, the output options of the newly developed tool are described.

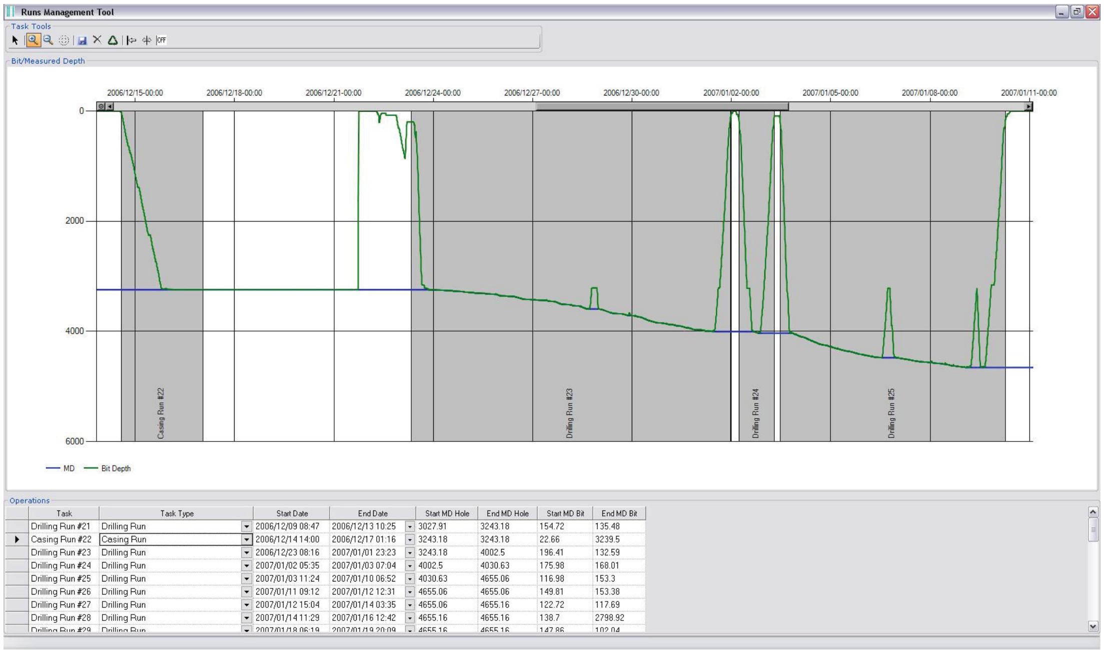
## ***Output Options – TaD Tool***

For proper field testing, the graphical visualization interface had to be built according to the ideas and specifications summarized during the first phases. This chapter describes the output options of the prototype according to the already described and additional new specifications.

The interface developed can be seen below. It is important to mention that the system was designed to act as a focal tool for all T&D related monitoring and optimization. The only requirement to run the tool is a computer with an internet connection. This makes the tool completely independent of where the user is located, as the data is access able all time. To do so, the user only has to select the well (scenario) of interest from the 'File' menu. Once a well has been selected, there are three plots available: the two 'Analyses Windows' (for hook load and torque) and the 'Runs Management Tool' (RMT).

## Runs Management Tool (RMT)

In order to avoid confusing unclear plots due to too many data points (especially for long wells), a grouping of the different operations was necessary. The concept of having T&D values grouped for individual BHA runs seemed to be the most appropriate solution for monitoring trends. In order to avoid manual interventions by the user, an additional OpRec rule was developed. This rule was designed in a way to detect each BHA run (casing, drilling, conditioning, etc.) of a well automatically. For visualization of the runs, the RMT was implemented in the TaD tool. The tool allows manual adjustments of runs and its parameters (e.g. start time, duration, type, etc.) as well as defining new runs manually. Furthermore, it shows the actual hole and bit depth, which can be tracked in real-time as every 60 seconds a new value for each channel is added. The RMT for the 'Testwell' is shown below:



| | Task | Task Type | Start Date | End Date | Start MD Hole | End MD Hole | Start MD Bit | End MD Bit |
|---|---|---|---|---|---|---|---|---|
| | Drilling Run #21 | Drilling Run | 2006/12/09 08:47 | 2006/12/13 10:25 | 3027.91 | 3243.18 | 154.72 | 135.48 |
| ▶ | Casing Run #22 | Casing Run | 2006/12/14 14:00 | 2006/12/17 01:16 | 3243.18 | 3243.18 | 22.66 | 3239.5 |
| | Drilling Run #23 | Drilling Run | 2006/12/23 08:16 | 2007/01/01 23:23 | 3243.18 | 4002.5 | 196.41 | 132.59 |
| | Drilling Run #24 | Drilling Run | 2007/01/02 05:35 | 2007/01/03 07:04 | 4002.5 | 4030.63 | 175.98 | 168.01 |
| | Drilling Run #25 | Drilling Run | 2007/01/03 11:24 | 2007/01/10 06:52 | 4030.63 | 4655.06 | 116.98 | 153.3 |
| | Drilling Run #26 | Drilling Run | 2007/01/11 09:12 | 2007/01/12 12:31 | 4655.06 | 4655.06 | 149.81 | 153.38 |
| | Drilling Run #27 | Drilling Run | 2007/01/12 15:04 | 2007/01/14 03:35 | 4655.06 | 4655.16 | 122.72 | 117.69 |
| | Drilling Run #28 | Drilling Run | 2007/01/14 11:29 | 2007/01/16 12:42 | 4655.16 | 4655.16 | 138.7 | 2798.92 |
| | Drilling Run #29 | Drilling Run | 2007/01/18 06:19 | 2007/01/19 20:09 | 4655.16 | 4655.16 | 147.86 | 102.04 |

Figure 25: Runs Management Tool

## Hook Load Analysis

In the 'Hook Load Analysis' the specified load over depth plots can be generated. In this view the simulated curves and the actual values can be plotted above each other for the available BHA runs.

This is done by picking the desired runs and operations in the properties window on the right side of the 'Hook Load Analysis' screen.

The figure below shows the window with the operations that can be visualized for analysis:

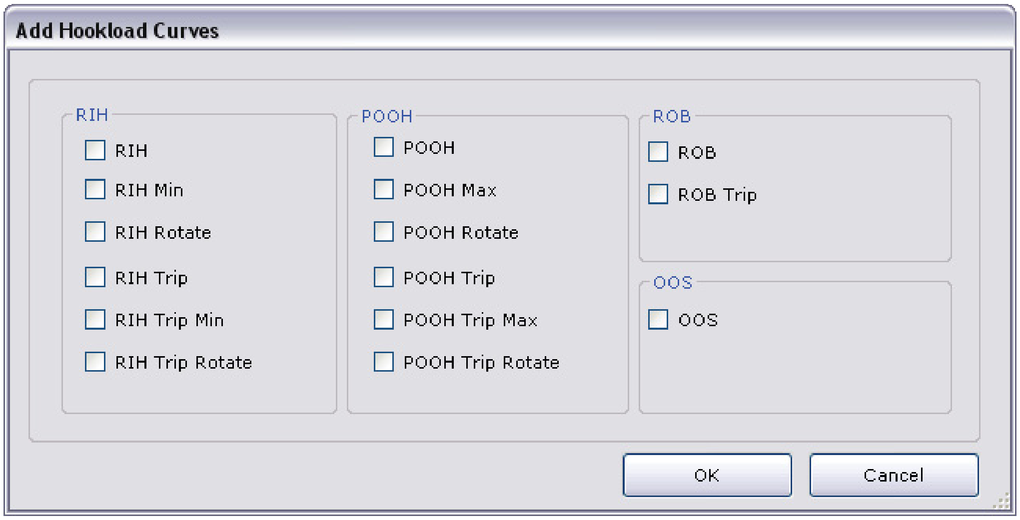


Figure 26: Available hook load operations in TaD

Figure 27 is a plot created with the TaD tool. It shows simulated curves for a 12” hole phase with a friction factor range of 0.0 to 0.5 for both, RIH and POOH. In addition, the actual operations RIH and POOH while tripping with a drilling BHA are plotted in blue and red circles. The plot area is automatically refreshed every several seconds. Every operation conducted at the rig site is then automatically added to the plot without any need of human intervention.

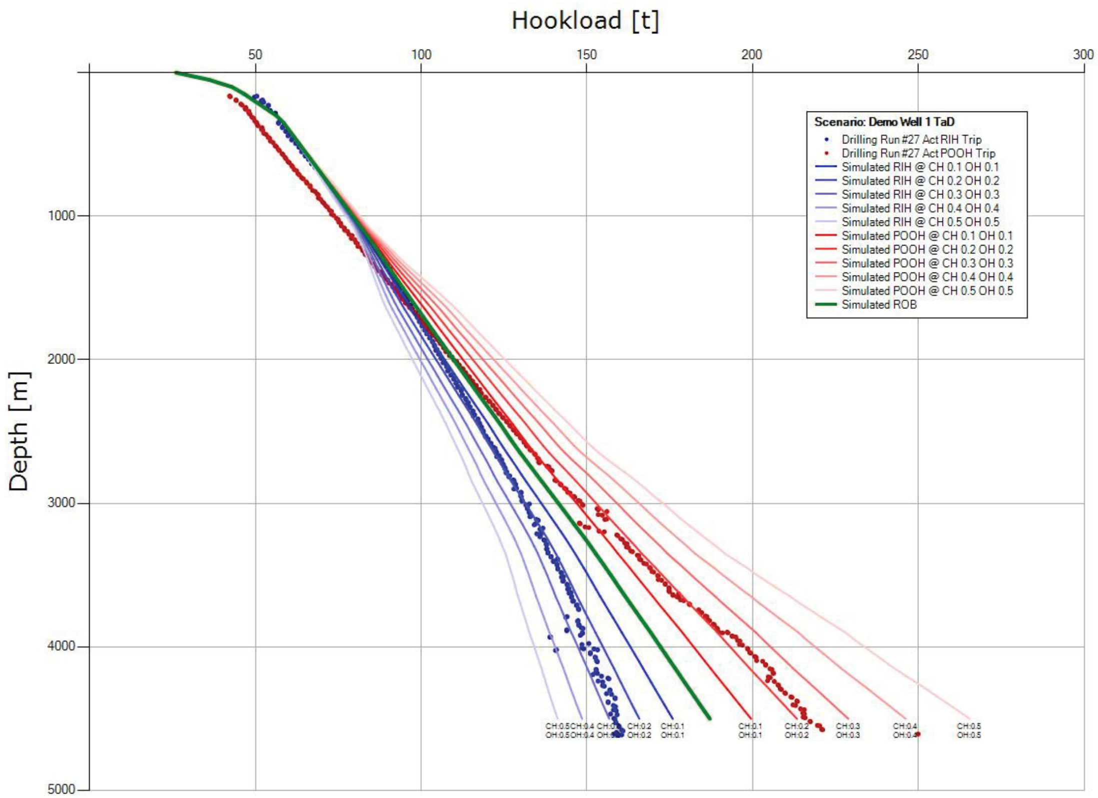


Figure 27: Trend analysis for surface hook load over depth – 12" phase

## Torque Analysis

The 'Torque Analysis' works very similar to the 'Hook Load Analysis'. One difference is that instead of hook load, the actual measured values for torque are plotted over the imported simulation models. As torque cannot be present without drill string rotation, the differentiation between the operations RIH, POOH and ROB with and without rotations was not necessary. The next figure shows the available operations for trend analysis:

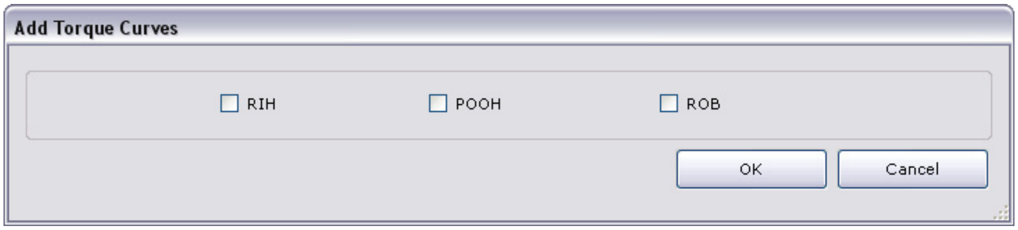


Figure 28: Available torque operations in TaD

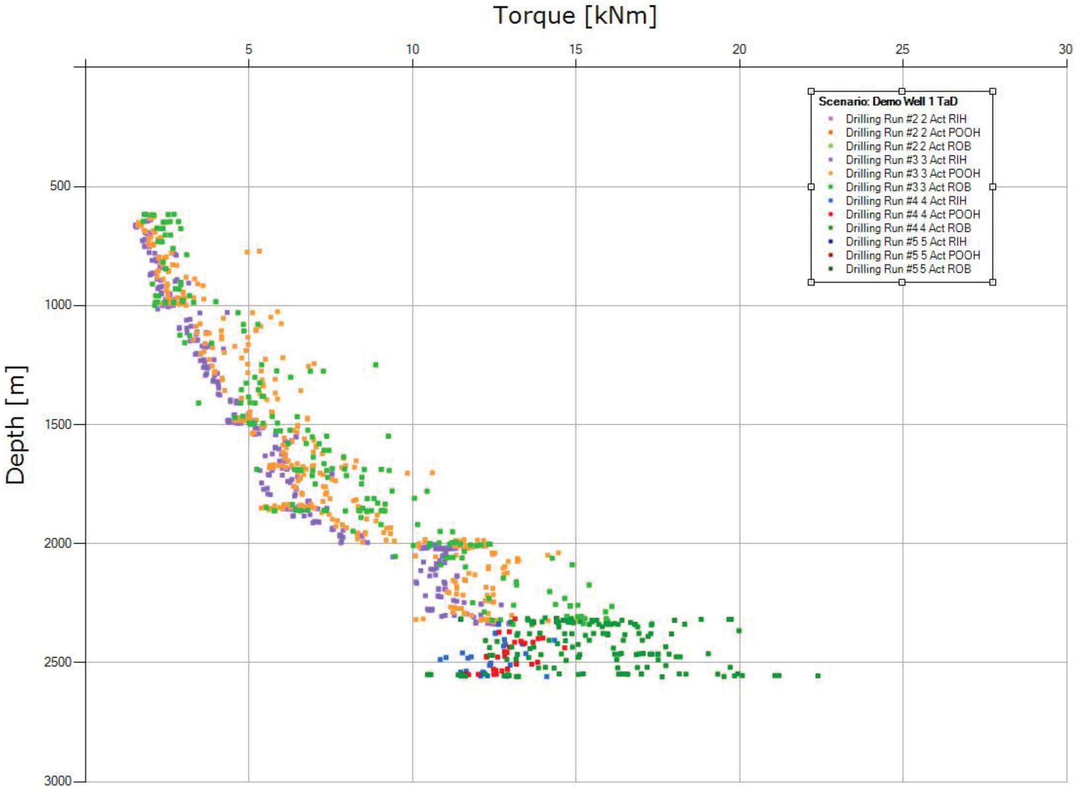


Figure 29: Trend analysis for surface torque over depth – 17 ½" phase, 4 drilling runs

As one can see in the figure above, different intensities in colors are used for the values plotted. Values for more recent BHA runs are darker in color than ones further in the past. This applies for both types of analyses.

In addition to these curves, annotations and formations can be entered into the system for visualization. This was a highly required feature as T&D mostly depends on the formation drilled and tripped through. Furthermore, annotations for the highlighting of critical points or trends can allow different users at different locations to exchange their interpretations and subsequent decisions. A plot including formations and annotations can be seen on page 62.

## Phase III - Testing and Evaluation

The final part of the tool development consisted of an extensive testing and evaluation phase. This field test was conducted by two drilling engineers, one software tester and the responsible software engineer. The well selected for the test was a three months land drilling operation with suitable inclination (> 20°) and depth (~ 5500 m). Special focus was placed on the real-time applicability and the T&D results.

In order to assure that the results generated with the new rule and plotted in the TaD tool are correct, a real-time data plotting software was used.

During the first testing of the prototype by the responsible drilling engineers, the following screenshot came up:

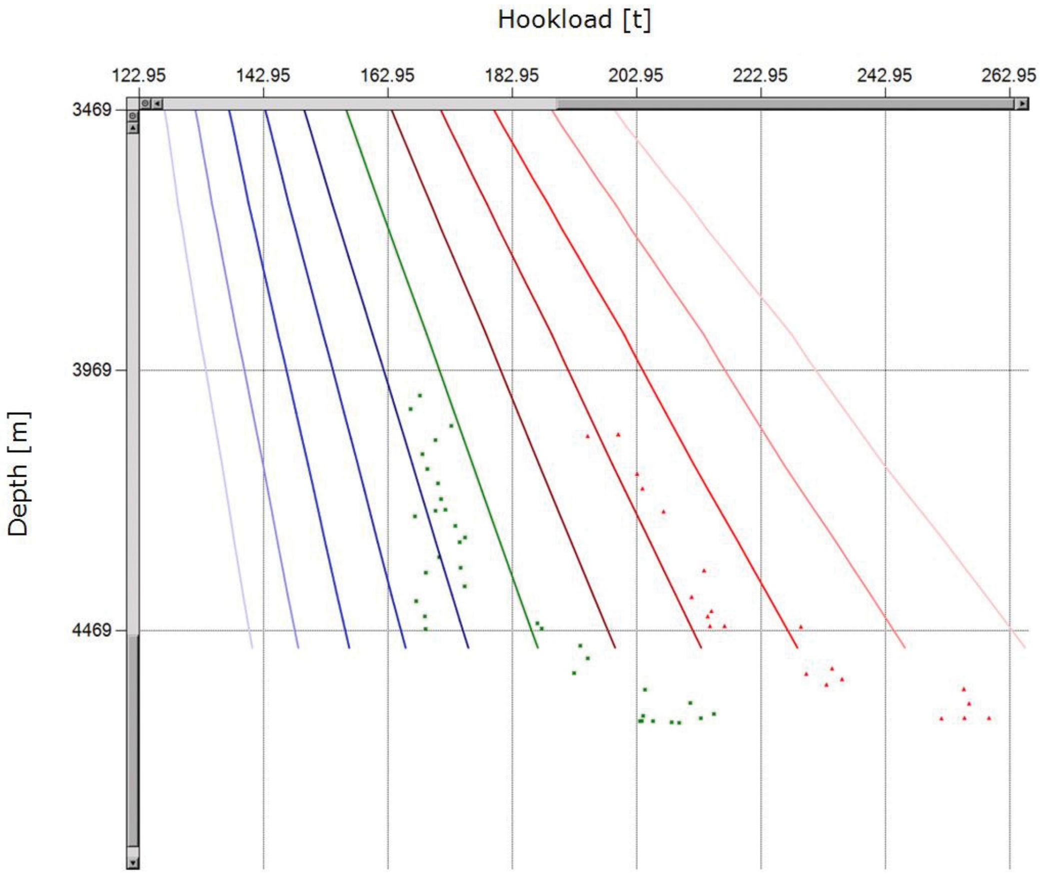


Figure 30: POOH and ROB while drilling

The actual points for the operations POOH and ROB were plotted over a set of friction factor curves for the 12" phase. In the figure above a clear trend can be seen for these two operations towards higher friction factor curves. From 4000 to 4400 meters the actual points were consistently around a friction factor of about 0.23. As depth increased, also the friction factor increased to more than 0.4. This trend in getting more and more overpull after a stand was drilled down, indicated with the TaD tool, needed to be verified.

Due to badly mismatching values for actual versus simulated POOH and ROB, the engineers believed that that the rule did not fit the specifications. An extensive test with the use of the real-time sensor data (sequence of screenshots below) was used for the purpose of showing that the values are correct.

The same increase as in the TaD tool can be seen in the hook load channel measured by the mud logger. Starting with values around 225 to 230 tons at a depth of 4500 m, the hook load increased to more than 260 tons. The red lines in the screenshots show the value of the median calculation of the OpRec rule developed for the TaD tool.

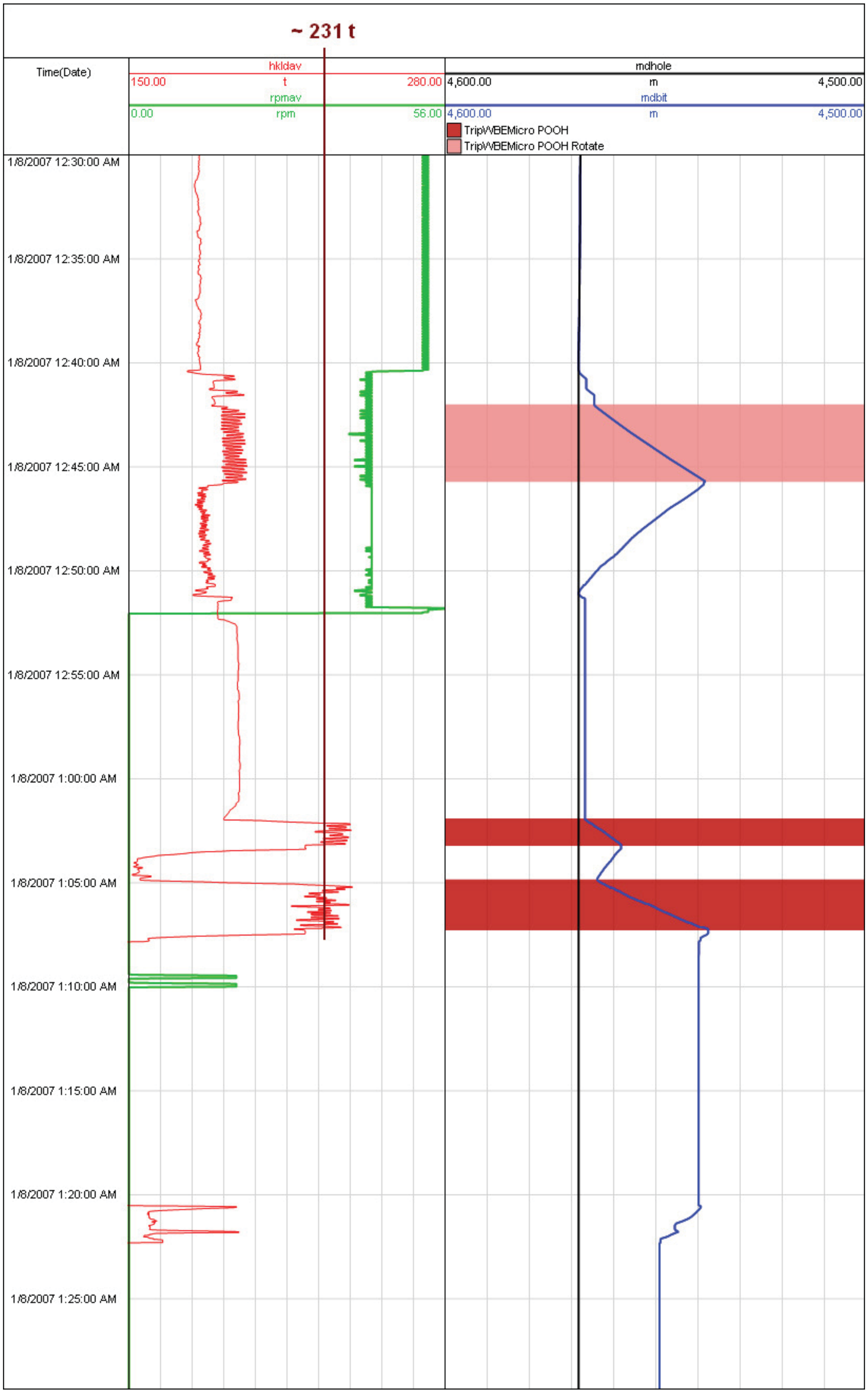


Figure 31: POOH - hook load verification (1)

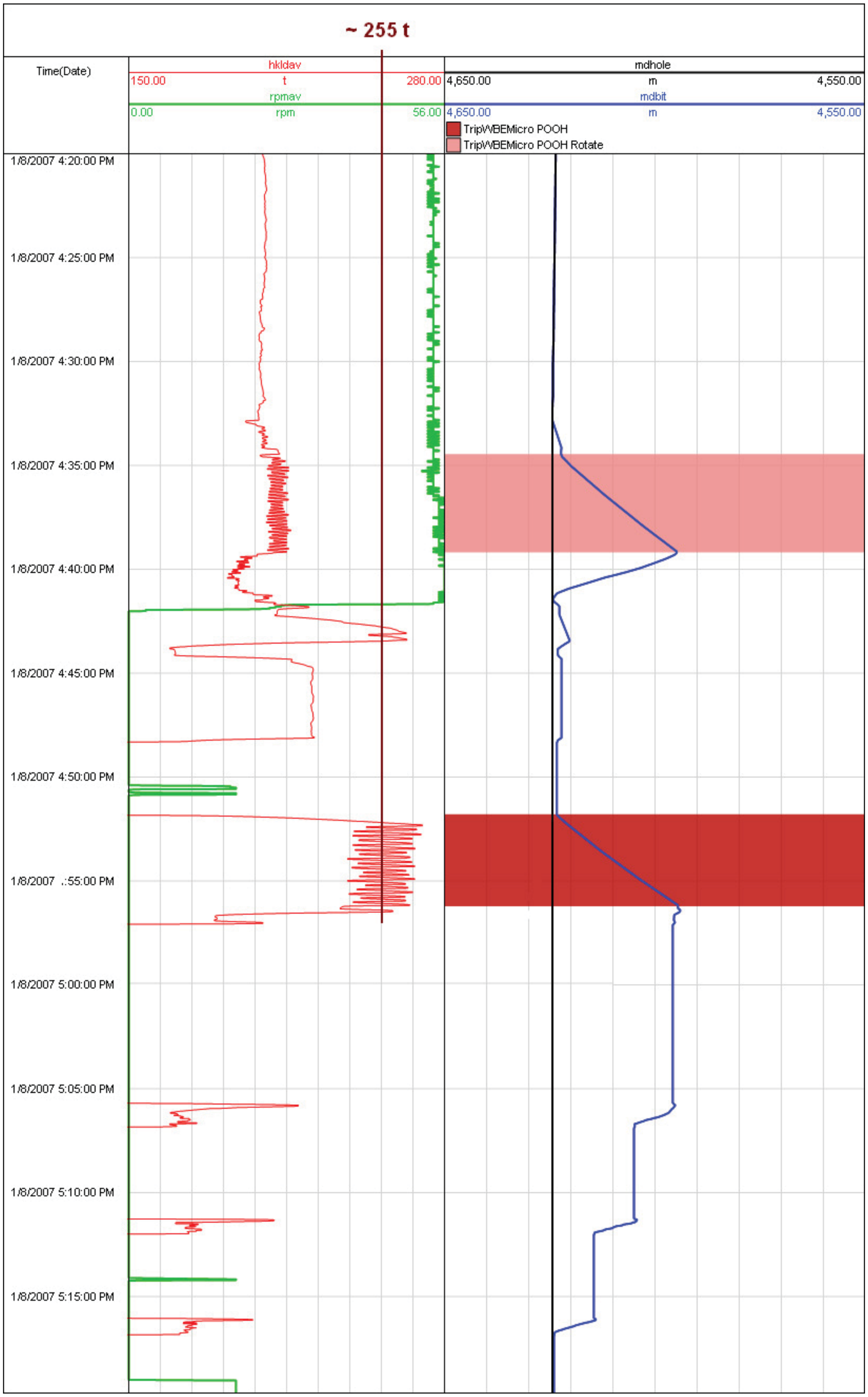


Figure 32: POOH - hook load verification (2)

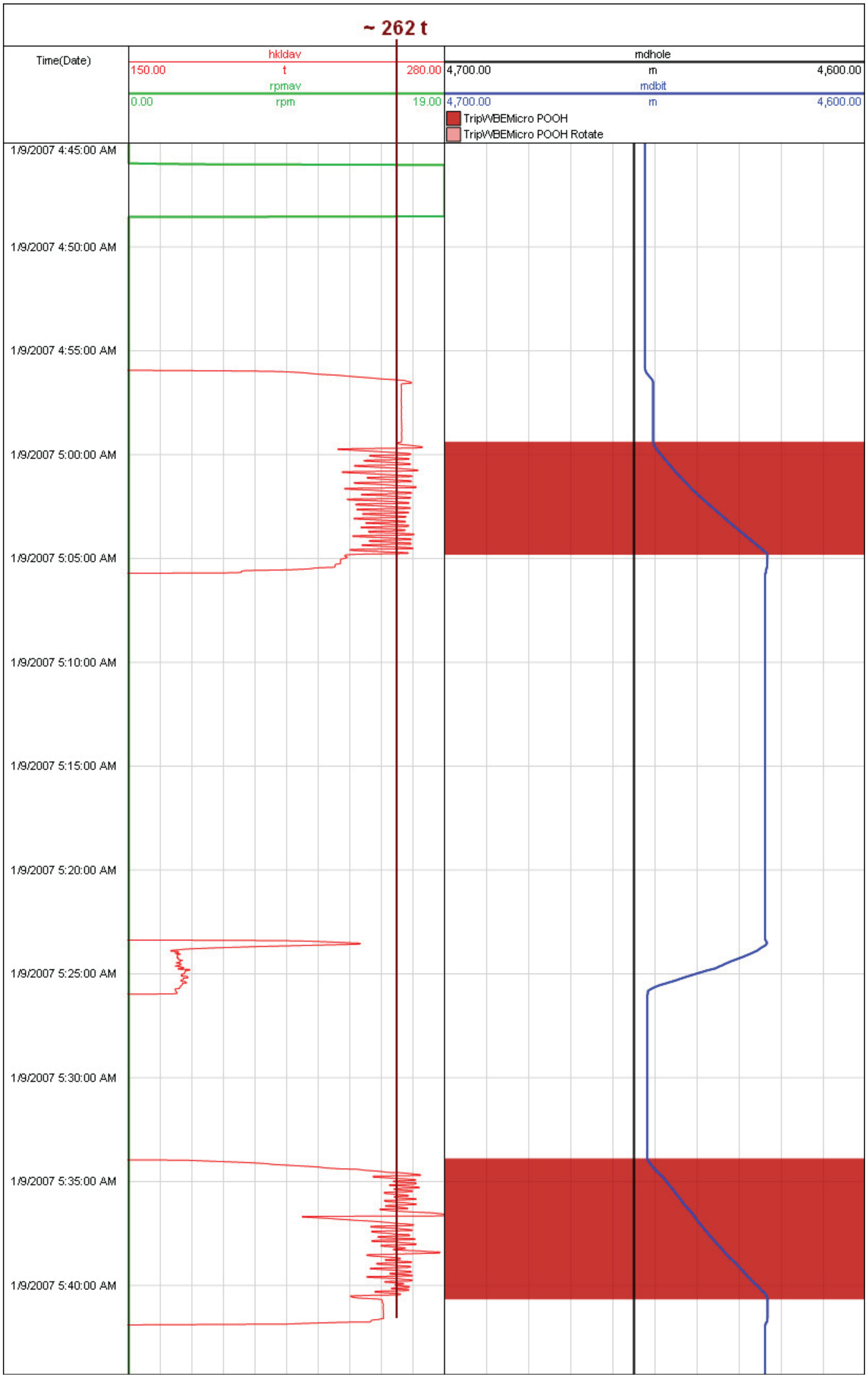


Figure 33: POOH - hook load verification (3)

Furthermore, the following behavior of the POOH and RIH curves could be observed while drilling and tripping in depths below 1500 m:

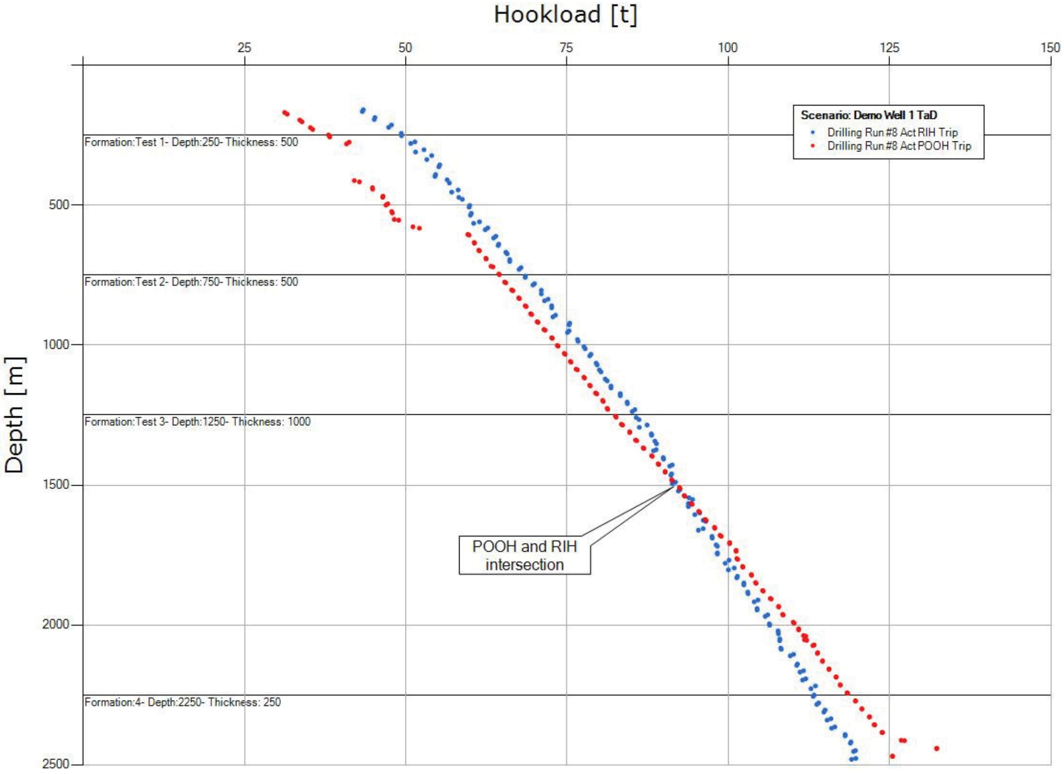


Figure 34: Hook load intersection of POOH and RIH

As the figure above indicates, the curves for POOH and RIH intersect at a certain depth below which the hookload while running out is lower compared to the one while running in hole. As this is in contrast to the physical laws stated in the Appendix of this thesis and also because this phenomenon did not occur on every rig tracked, further investigation was necessary. The real-time plot of sensor data shown below, verified that the calculation is correct and that there must be some problem with the hook load sensor or measurement process itself.

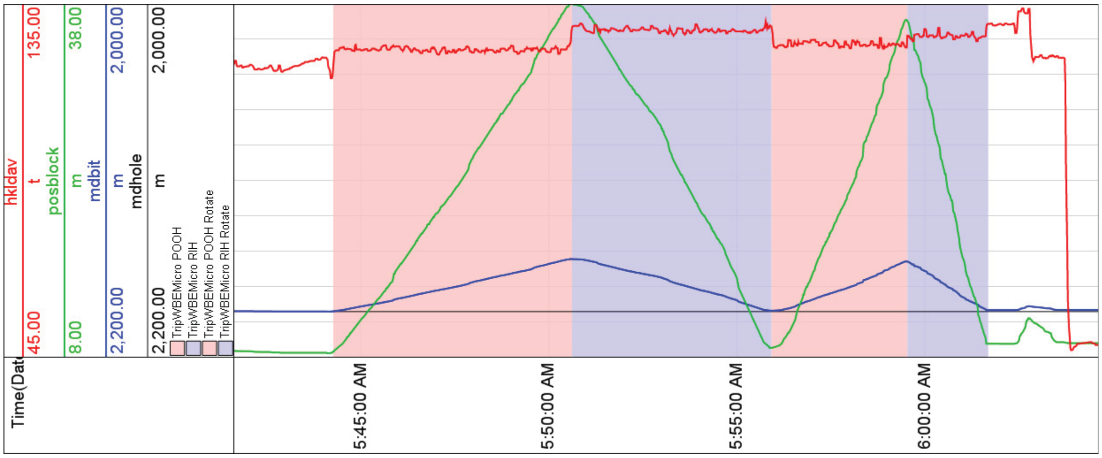


Figure 35: Higher hook load while RIH compared to POOH

Figure 35 above verifies that the hook load was constantly higher for the two times where the string was pulled out of hole (red section) compared to where it was run in hole (blue section).

A possible reason for this phenomenon could be that the hook load is measured at the dead line. This can result in lower values for POOH due to the lesser amount of drilling line that is released off the draw works when the block is on top. In contrast to that, when the block is at the bottom, a maximum of drill line is released off the draw works. If the sensor, which is attached to the dead line, does not take the weight if this additional drill line into account, such an incorrect pattern for T&D can result. The magnitude of this shift in hook load is therefore based on the size and weight of the cable used. One issue which could not be explained is that the hook load remains nearly constant while the string is moved. In no case was an expected steady increase or decrease in hook load due to the weight of the cable observed.

As this problem does not seem to be considered in the measurement process of some data providers, an additional parameter was included in the T&D rules. This allows compensating such a phenomenon by simply adding or subtracting a pre-set value from the calculated one.

# Phase IV – Implementation and Feedback

As the intensive field testing showed that the generated results were correct as well as that the real-time applicability is given, several analyses were made and feedback was gathered. Furthermore, the tool was finalized and released to a company where it was used for real-time monitoring of T&D for another two 5000 m wells.

In particular the workflow between the drilling engineers and the field personnel had to be optimized. During the evaluation and implementation phase, the operations centre with the drilling (planning and optimization) engineers developed to the main work station accessing the real-time system. It furthermore turned out to be the focal point for all relevant information about the status, the history and the planning of the current operation related to T&D. Basically the engineers in the office have to gather all the necessary information for the simulation models as well as to identify situations that could result in upcoming problems during drilling, tripping and casing operations. Finally, the flow of information had to be defined. Following a particular line of communications was specified once the user has identified a critical situation:

The reported information would have to contain information about the type of the emerging situation, including the fact why the operation differs from the normal process. The situation is then discussed within the drilling team and a reaction to this critical development needs to be worked out. This reaction is communicated to the company man by the drilling engineer. Then the user of the TaD tool has the responsibility to monitor the effects of the countermeasures in real-time. The user would also be in the ideal position to be responsible for the production of lessons learned after the effects of the decisions made have been tracked. These lessons could then be used by the drilling engineer for planning purposes of upcoming wells.

## *Monitoring while Drilling*

During drilling operations it is important to track the RIH and POOH weight without rotation. Unfortunately, these operations are rarely done after a stand has been drilled down as it can lead to critical situations. Generally the best procedure is to move the string while rotating and pumping (reaming). Nevertheless, to monitor and judge the downhole situation it would be much better to have the loads from string movement without rotation available. Only then full friction is acting on the string and the hook load is on its maximum. Generally it needs to be stated that proper optimization while drilling can only be done if values for real RIH and POOH are available.

The series of chapters below gives an overview on the problems that can be detected in the wellbore due to increased friction. Based on the feedback gathered from drilling engineers, possible reactions and counteractions are mentioned.

### Cuttings Bed Build Up

A build up of a cuttings bed in the annulus can lead to severe problems, especially in highly inclined and horizontal wells. Such an accumulation of cuttings can act on the drill string in a way that the friction permanently increases. In the worst case this can result in a stuck pipe situation where the string gets totally locked up in the hole. In order to avoid such costly trouble time, constant real-time monitoring of trends in torque and drag is a key element. Proper counter measurements and decisions can then be made at an early stage.

### Differential Sticking

Differential pipe sticking is another phenomenon that increases the friction (pseudo friction) between drill string and wellbore wall. Due to the pressure difference between wellbore pressure and formation pressure during overbalanced drilling operations, it can happen that the string is forced to the wellbore wall. Such a situation would increase the normal force and therefore the friction.

As stuck pipe situations can develop over hours, it is important to follow the trend of the out of slip hook loads in real-time. As already mentioned, the OOS is the maximum hook load value recorded over a time frame of 20 seconds after a slip to slip connection was made.

Monitoring of these values over measured depth can allow early detection of an increasing trend and early counter actions can avoid expensive sidetracking.

### Wellbore Conditioning

A common, but necessary operation is to ream a section that has been drilled in order to improve the downhole condition. In order to avoid such time consuming operations to be conducted in an excessive way, the actual improvement needs to be monitored. The TaD tool allows real-time tracking of these operations as they are conducted.

At the beginning of an extended wellbore conditioning operation, the hook load is expected to be quite significantly away from the center model line representing the hook load during ROB. After every reamed stand (up- or downwards), the measured hook load should move more and more to the center model line. Once the measured hook load values are at a level that is already indicating a very smooth downhole situation, time may be saved by stopping the reaming operation earlier.

## *Monitoring while Tripping*

Real-time monitoring of T&D is not only important while actually making hole but also during tripping operations. The reason for this is that vital information about the wellbore aging and the behavior of trouble zones over time can be gathered. Following problems related to wellbore aging can be tracked:

### Forming Ledges

Ledges and their trend over time can easily be detected while running in the hole with a BHA. As a stand of pipe is run into the hole, a ledge would suddenly decrease the hook load for this stand due to the additional resistance acting. Also the minimum hook load measured during the running of this particular stand ('RIH Trip min') would be much lower compared the average and the normal.

Especially the trend over several trips is of importance when monitoring the forming of ledges. If the median and the minimum hook load for 'RIH Trip' further decrease in that certain depth over later trips, the problem is getting worse. If the hook load gets back to normal over later trips, the situation is getting better.

### Emerging Key Seats

In contrast to ledges, key seats can be detected while tripping out of hole. This can be done by monitoring any increase in hook load while pulling the string. The reason for such an increase in drag when running through a section with a key seat is that the string can hang up in this critical area.

Especially when depths with a high risk of key seats are known, these sections shall be closely monitored in real-time. Again, it is important to monitor the development over time to get information if the problem gets better or worse.

### Tight Hole Problems

Problems due to a tight wellbore are quite similar to the ones of key seats. A tight hole that closes the annular space around a tubular assembly that is located in the wellbore can also be detected by monitoring trends in hook load. In contrast to the key seats where the detection is only possible while pulling out of the hole, wellbore instabilities can also be observed while tripping in. During both operations, the hook load is expected to diverge from the normal trend. When pulling the string, the hook load will increase, whereas while tripping in, the hook load will be lower than normal. If such a behavior can be observed, the particular formation at this depth shall be watched with more attention. As with the other problems described before, the situation downhole gets worse if the deviations from normal become larger.

A possible solution for such a tight hole problem is to ream through the particular section to improve the hole's quality until the hook load is back to normal (at ROB level). The improvement can be tracked with the real-time TaD tool and the time frame for this operation can be optimized.

## Monitoring of Casing & Completion Runs

Before a casing or completion string is run into the open hole, it is recommended to analyze the T&D tripping data of previous drilling and conditioning runs. This is especially the case for highly inclined and horizontal wells where the casing string can easily be locked up in the hole if the wellbore is in a bad condition. In addition, the analysis of all available well data can give crucial information about the necessity of spending additional time on wellbore conditioning before actually running the casing.

With the use of the TaD tool it is very easy to analyze the tripping of BHA's that were run through the open hole section to be cased. Importantly, these runs can give information on zones where the casing run can reach its limits. As a consequence, it is very important to analyze the trends in measured hook load compared to the simulated models.

If any inconsistencies are detected, further information from other drilling data can be gathered (e.g. caliper log) to analyze the reasons. This additional information can assist in more accurate identification of where the casing run may encounter problems. With this information at hand, actions can be discussed to improve the situation in an identified critical zone.

Once the decision is made to run the casing or completion into the hole, TaD allows real-time monitoring of the run in the same manner as already described in the chapter Monitoring while Tripping.

The drilling engineers who tested the tool during the evaluation phase gave the following feedback on the casing monitoring procedure. They recommended running every casing job optimization directly at the rig site. The reason for this is that while running casing the interaction between drilling engineers and supervisors needs to be at a frequent and high level. Furthermore, during running casing, additional factors need to be accounted for. Such parameters (e.g. partially filled casing string, changing fluid level in casing, etc.) have a high impact on the simulation models that are loaded into the TaD tool. In order to be able to adjust the models whenever necessary, close cooperation with the supervisors is of high importance. Otherwise it may become quite hard to distinguish changes in friction factor from changes induced by operational measures. Once real changes in hook load are observed, the casing run can already be stopped at an early stage. A stuck casing is something that really needs to be avoided because of the high tubular costs and the lost time. Furthermore, a casing cannot be rotated which would result in lower drag while moving the joints. As a consequence, analysis always needs to be made on the RIH (no rotation) curves. Once sharp decreases off the normal hook load trend are detected, the casing is under threat to be held up or to get stuck in the hole. Real-time monitoring and early counteractions are crucial tasks to successfully run a casing to total depth.

## Additional Feedback

During the implementation phase further feedback was gathered from the responsible drilling engineers. As the tool was used to monitor T&D for two deep wells (> 5000 m), the expectations on the feedback were very high. For one well, the tool was unfortunately implemented five days too late as following example shows:

The whole monitoring system was installed and provided during the logging phase prior to the casing of the 12 ¼” section. The purpose was to monitor T&D for the imminent 9 5/8” casing run. As the 12 ¼” open hole section was drilled without any problems from 3003 to 4430 m MD, no additional time was spent on wellbore conditioning. Once the casing float shoe passed the 3003 m, circulation was broken and the string was washed down further. At a depth of 3300 m the string was held up as the figure below indicates. It took 17 hours to get the casing string beyond this depth.

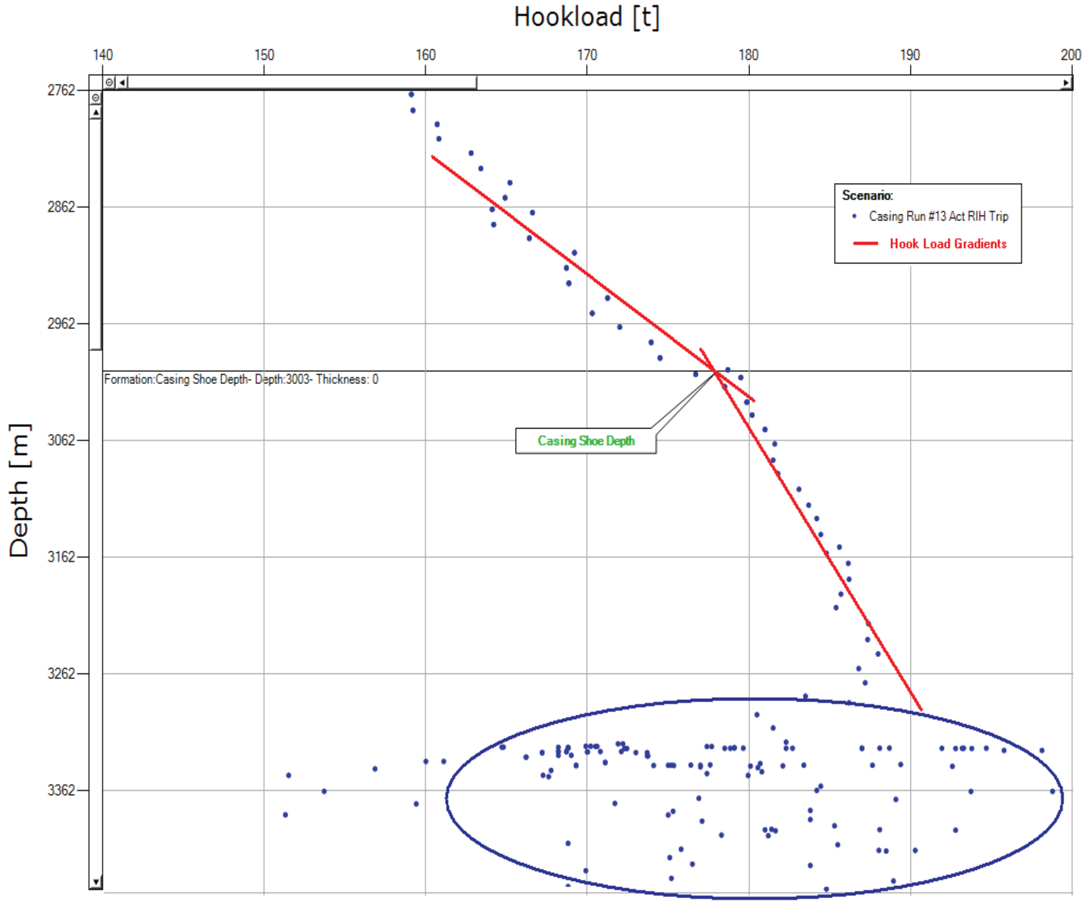


Figure 36: T&D monitoring of a 9 5/8” casing run

As one can see in Figure 36, the trend (gradient) in hook load decreased immediately once the bottom of the casing entered the open hole section. The casing was run further into the hole but got totally held up in a depth of 3300 m (indicated by the horizontal series of blue dots at the same depth and the blue circle).

Finally the caliper log was interpreted in order to find the reasons for this casing string lock up. As there was no obvious concern mentioned by the drillers who drilled and tripped through this section, the reason for this situation was quite unclear in the beginning.

The caliper log conducted before the casing was run in the hole, showed a clear increase of hole size with interbedding ledges at a depth of about 3290 to 3300 m. The maximum caliper measurement increased from 12 ¼" up to 16" whereas the minimum caliper showed much smaller and fewer deviations. According to the responsible drilling engineer, this indicated washouts in an elliptical shape. The rest of the wellbore seemed to be in a good condition. Furthermore, this critical section had a 5.5° inclination due to the close kick off point at 3200 m. As a consequence the dogleg severity increased up to 1.7 °/30m. The combination of these conditions (washouts together with a high building angle) seemed to be the reason for the casing to hold up.

Due to the fact that this critical area with ledges was not detected with 'normal' methods, the decision was made to load the data for the whole well into the T&D database. As the system is also capable of loading the necessary sensor channels in history mode, even previously drilled wells can be re-processed and analyzed for T&D related problems. This was done for the well with the trouble zone in the 12 ¼" section and took only a few hours. If the results shown below would have been available for the responsible engineers and supervisors, the decision to run the casing might have been reviewed.

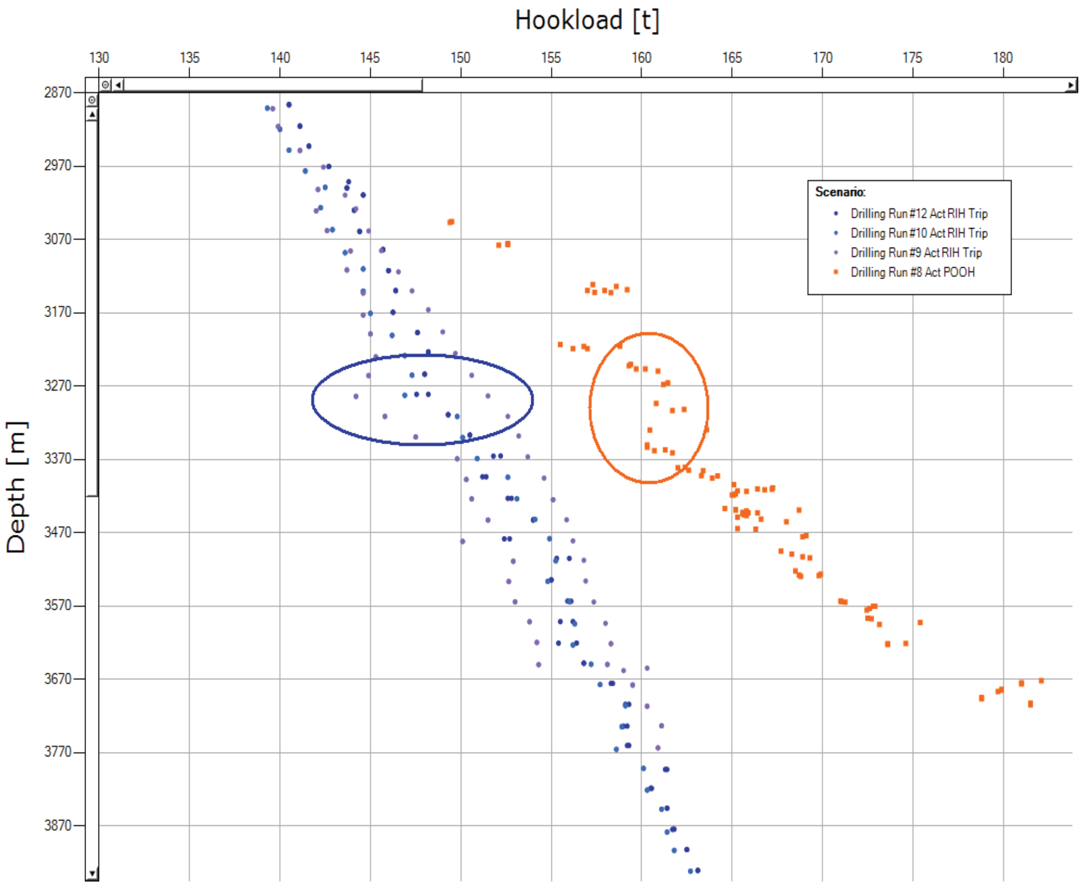


Figure 37: Hook load analysis for drilling runs prior to hold up 9 5/8” casing run

The figure above shows a TaD ‘Hook Load Analysis’ of the three drilling runs prior to the casing run. For all of them the RIH while tripping curves are displayed (‘RIH Trip’ – different intensities of blue). In addition, the POOH while drilling (POOH) curve for the run where this critical interval was drilled through, is shown in orange. Both types of curves clearly show the presence of some irregularities between 3290 and 3300 m MD.

As stated before, forming ledges can be detected during running in hole. Once the bit reaches the critical zone, the hook load for the current moving stand will suddenly decrease and deviate from the normal trend.

This behavior is indicated with a blue circle in the figure above. Although the situation seemed to become better, due to the less sudden decrease in hook load over time, the casing string was held up in the wellbore. Furthermore, the hook load values while POOH during the drilling of this section showed increased friction (orange circle).

According to the drilling engineers, operations would have been re-designed if this information would have been available already prior to the casing run.

This is only one of several cases where the TaD tool proved its correctness and operational applicability. For all of the wells monitored, the time spent on wellbore conditioning was optimized and critical trends were detected at an early stage.

# Conclusion

There are several approaches available in the oil-field industry allowing successful real-time monitoring of torque and drag. Nevertheless, there are weak points and limitations which have been addressed throughout the thesis. The three most important ones are: The visualization method used to present the results to the user, the absence of an automated algorithm differentiating between the various rig operations based on real-time sensor data, and the amount of rig time it takes to actually get the raw values for further calculations.

All three of them have been taken into account during the design of the new software application. Because the tool had to be developed not only for drilling engineers, but for all personnel involved in the well construction process, the importance of developing a straightforward visualization method was very high. In order to prevent misinterpretations and wrong assumptions about the wellbore health's status, it was preferred to stick with proven T&D visualization techniques instead of showing the same information simply in other, more complex ways.

Besides the surface value over measured depth plot, the automated operations differentiation is the key element of the newly developed application. The possibility to get torque and drag values while drilling, tripping (drill pipe, casing, tubing, liner) and wellbore conditioning differentiated, confirmed the real-time applicability. All this was achieved by the implementation of an automated routine using real-time sensor data as input. The main advantage is that there is no human intervention or additional rig time needed to run the system. As a consequence, the main requirement of avoiding a time-consuming on-site test was fulfilled. It is important to mention that although the used concept of tracking torque and drag is straight forward, the developed system is very complex. The combination of real-time sensor data, torque and drag simulation models and the automated operations recognition algorithm based on logical rules, resulted in an extensive software application.

It was very important, that the values visualized with the newly developed tool have been proved for their correctness. Because of the ongoing tendency in using hand taken values, manually drawn into a graph, instead of switching over to new approaches, the tool is examined with care. Drilling engineers currently using the tool in their daily monitoring routine for drilling and completing a campaign of several extended reach wells, confirm this tendency. Although they have proven several times that the results presented with the tool show real values from the driller's console, the challenge is not yet over. Even the saved rig time as well as the automatic visualization is not yet reason enough for drillers and tool pushers to trust an automated software routine.

Nevertheless, the monitoring of trends in actual versus planned met with optimization engineer's approval in order to improve wellbore conditioning operations. Excessive reaming and washing can be avoided as low deviations from planned torque and drag may be an indication for a good hole quality. As a consequence, hidden lost time can be saved.

An additional advantage is that the application is not limited to be run from the rig-site. The possibility to broadcast the data to the office as well as to real-time operating centers all over the world, allows drilling engineers to actively monitor trends in torque and drag. As a consequence, upcoming critical situations can be detected earlier, allowing faster feedback on necessary counteractions.

The extensive field test has shown, that it is recommended to run the torque and drag tool in combination with a real-time sensor data plotting software in order to improve cause studies on shifting trends.

# Appendix

## Friction

Friction is a complicated phenomenon that is not fully understood up to now [12]. The origin of this force between two surfaces in contact is based on the molecular attraction of the atoms at the contact area. As friction is derived from the electromagnetic forces between those atoms, it is not a fundamental force.

At every surface area where two solid objects are in contact with each other, frictional resistance is present. This resistance depends on two factors, namely the force that presses the surfaces together as well as the roughness at the contact area. Because the pressing force is always perpendicular to the moving direction, respectively friction resistance, it is called the normal force $F_N$. The roughness is also referred to as the coefficient of friction or friction factor ($\mu$). This parameter is an empirical property of the contact materials. Therefore, the friction factor depends on the condition and composition of the contact areas.

Based on this information, the equation for the friction force between two solid surfaces, also known as Coulomb friction, can be written as following:

$$F_F = \mu \cdot N \qquad \text{(Standard Friction Model)} \qquad \text{(Eq.2)}$$

Where $F_F$ or $F_{friction}$ = Force exerted by friction [N]

Where $\mu$ = Friction factor [ ]

Where $N$ or $F_N$ = Normal force [N]

As one can see, the friction force is independent of the area between the two objects in contact. Figure 38 shows a solid body on a horizontal surface with all the forces acting on it. Besides the previously mentioned friction and normal forces, there are also the applied force F and the gravitational force $F_G$ acting.

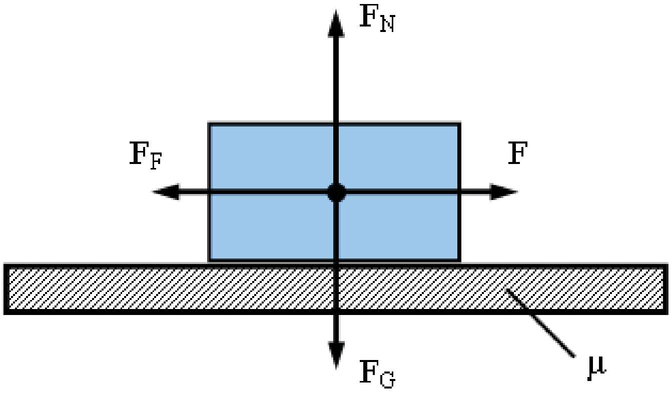


Figure 38: Solid body on a horizontal surface with acting forces

The following additional equations apply when talking about friction:

$$F_G = m \cdot g \qquad \text{(Eq.3)}$$

$$F_G = N \qquad \text{(Eq.4)}$$

Where $F_G$ = Gravitational force [N]

Where $m$ = Mass/buoyed weight of solid body [kg]

Where $g$ = Gravitational acceleration [ $9.81 m/s^2$ ]

As already stated, the frictional force is presumed to be proportional to the coefficient of friction. However, the amount of force required to move an object that is in rest is usually greater than the force required to keep it moving at a constant velocity. This fact requires the definition of three different types of friction with their own different friction factor.

## Types of Friction

### Static Friction

Static friction applies if two bodies in contact are at rest relative to each other [13, 14]. This type of friction force increases with the applied force in order to prevent any motion up to some certain limit where motion will occur. This threshold of motion due to the interlocking of the surface irregularities is characterized by the coefficient of static friction. As it can be seen on Figure 39, the static friction factor is higher than the kinetic one where the surfaces are in relative motion to each other. Below the transition point, there is a linear relationship between the applied force F and the friction resistance, which means that every increase in F results in a counteraction by $F_s$ with the same magnitude. When the critical point, the threshold of motion, is reached, the applied force is equal to the maximum static friction.

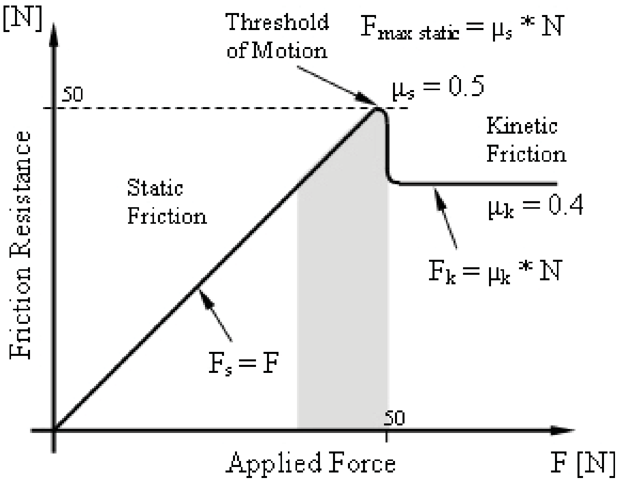


Figure 39: Transition from static to kinetic friction

### Kinetic Friction

Once the applied force is larger than the maximum static force the friction type changes into kinetic mode. Due to a force F acting on one side of the solid body, which is now large enough to overcome the resistance, the body starts to move. As already stated, the kinetic friction factor $\mu_k$ is smaller that the static one. This margin is indicated with grey color in Figure 39. Due to the smaller kinetic friction factor, it is easier to keep a body in motion than to bring it out of rest.

The resulting friction resistance is almost constant over a wide range of low speeds and therefore independent of the velocity. As a consequence, the standard friction model (Eq.2) applies also for the kinetic mode.

### Rolling Friction

The third mode of friction is the rolling type. This mode is associated with the rotational movement of a circular object along a surface. Generally, the frictional force in rolling mode is less than that associated with kinetic friction. A typical value for the rolling friction factor is 0.001.

## *Normal Force & Drag*

Up to now, only the case of objects on horizontal surfaces was discussed. In such situations, the normal force is equal to the weight of the body and perpendicular to the frictional resistance.

If the object is on an incline, the normal force is not equal to the weight anymore. The same applies if the applied force acting on the object has components that are perpendicular to the surface.

The next figure shows a solid body on an inclined surface with all the forces acting on it in such a situation.

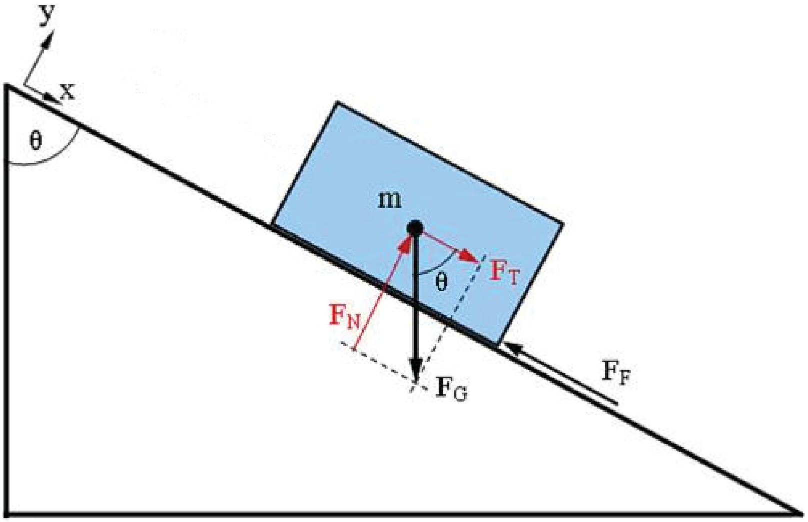


Figure 40: Object on an inclined surface

It is obvious that because of the inclination with a certain angle θ, the normal force does not equalize with the force that is induced by the mass of the body. As this weight needs to be separated into its two resulting forces, the normal force is lower compared to the gravitational force.

Following equations apply if an object slides on an inclined and straight surface:

$$F_N = F_G \cdot \sin\theta \qquad \text{(Eq.5)}$$

$$F_T = F_G \cdot \cos\theta \qquad \text{(Eq.6)}$$

$$F_F = \mu \cdot F_G \cdot \sin\theta \qquad \text{(Eq.7)}$$

Where $\theta$ = Inclination [°]

If the component of the gravity force down the incline is equal to the frictional resistance, then:

$$m \cdot g \cdot \cos\theta = \mu \cdot m \cdot g \cdot \sin\theta \qquad \text{(Eq.8)}$$

$$\mu = \frac{\cos\theta}{\sin\theta} = \cot\theta \qquad \text{(Eq.9)}$$

All these equations are of importance in drilling engineering when talking about torque and drag, as these parameters can become very critical. Whenever the drill string is lowered or raised in the wellbore, friction resistance is induced based on the theory described up to now. The next two figures are similar to Figure 40, but include the conditions for lowering and raising a section of pipe in an inclined wellbore.

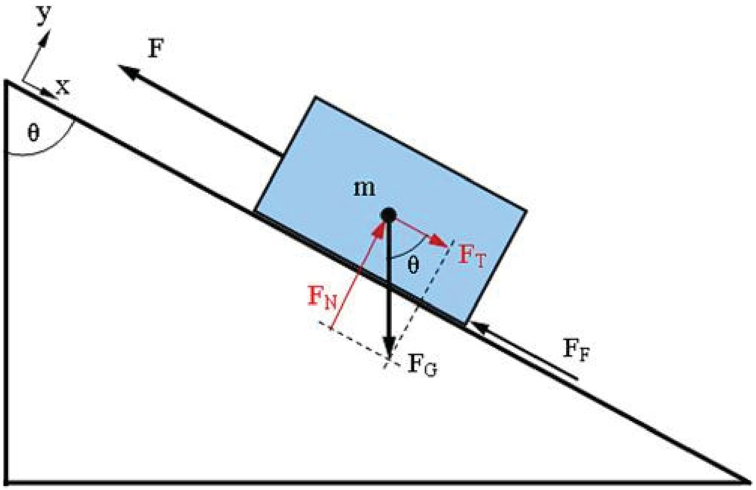


Figure 41: Lowering the drill pipe (RIH)

The picture shows the forces acting on the segment of pipe during the operation ‘Running In Hole’, which means that the drill pipe is lowered into the well. During this operation the frictional resistance works against the lowering process and reduces therefore the load carried by the hook. The following equation applies for this operation with respect to having a straight surface where only mechanical friction is acting:

$$F_{RIH} = F_G \cdot \cos\theta - \mu \cdot F_G \cdot \sin\theta \qquad \text{(Eq.10)}$$

Where $F_{RIH}$ = Force acting on the hook during lowering the drill string [N]

The opposite of lowering the string is the operation 'Pulling Out Of Hole', where the pipe is raised, as shown in the next figure, in an inclined well. Again the friction works against the desired process as the friction resistance works downwards and applies additional load that needs to be carried. The equation for this operation only differs from the previously formula above by the plus sign, as the friction resistance force is now added to the resulting weight.

$$F_{POOH} = F_G \cdot \cos\theta + \mu \cdot F_G \cdot \sin\theta \qquad \text{(Eq.11)}$$

Where $F_{POOH}$ = Force acting on the hook during raising the drill string [N]

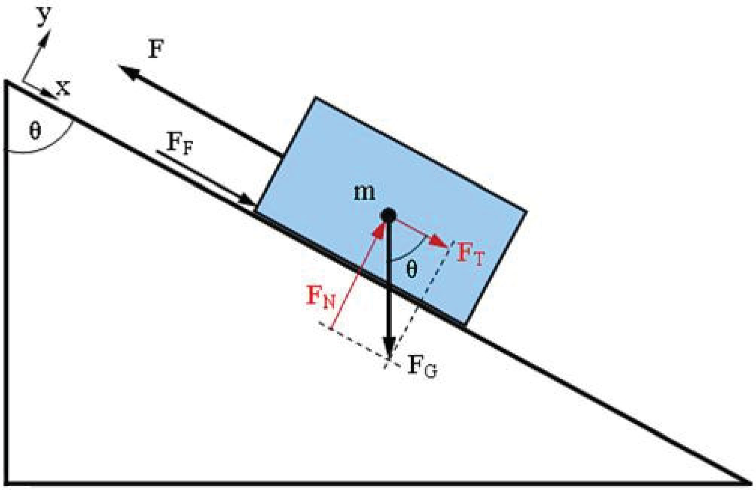


Figure 42: Raising the drill pipe (POOH)

For all the equations above, the angle of inclination θ has a large impact on the force F that is exerted on the hook.

Practical examples:

- If a complete vertical well is drilled, which means that there is absolutely no inclination, then the mechanical friction resistance can be neglected, as the friction term is zero ($\sin 0° = 0$).
- For wells with inclined sections ($> 0°$), the weight of the pipe in the hole to carry by the hook will decrease and the frictional resistance force will increase with higher angles.
- Finally, the case of having horizontal sections (e.g.: extended reach wells), results in frictional resistance forces only, as the weight of the pipe will be supported by the formation ($\cos 90° = 0$).

## Torque

The concept of torque is based on a force that is applied to a lever, as well as on the distance from the lever's base to where this force is acting.

In order to calculate the torque acting on a drill string when it is 'Rotated Off Bottom' (ROB), following equation can be used which is based on this $torque = (moment\ arm) \cdot force$ concept:

$$Tq = F_F \cdot \frac{d}{2} = \mu \cdot F_G \cdot \sin\theta \cdot \frac{d}{2} \qquad \text{(Eq.12)}$$

Where $Tq$ = Torque [$N \cdot m$], [$ft \cdot lbf$]

Where d = Pipe diameter [m], [ft]

The force acting in such a situation is the frictional resistance force induced by the contact of the pipe with the borehole wall. This means that in a theoretically straight and vertical wellbore, no torque will appear as the string would hang on the hook without touching the formation at the side.

Figure 43 shows the simplified case of where pipe and wellbore wall are in contact with each other. Furthermore, the forces and moments acting during such a situation are displayed.

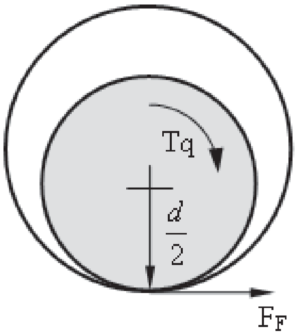


Figure 43: Torque acting on a segment of pipe during ROB (approximation)

This simplified case assumes that the pipe lies at the lowest point of the inclined borehole wall while it is rotated off bottom. In contrast to this approximation, the real case will look like as shown in Figure 44. Due to the rotational movement, the pipe will always tend to move up the borehole wall in order to balance out the forces. As one can see in the figure above, there is no force that balances the friction force $F_F$. The second case below, accounts for this and assumes equilibrium at an offset angle φ.

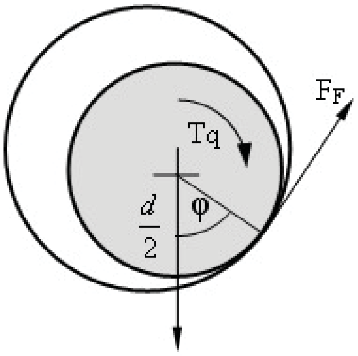


Figure 44: Torque acting on a segment of pipe during ROB (accurate evaluation)

The formula to calculate the torque for this more accurate evaluation is the following:

$$Tq = F_G \cdot \sin\theta \cdot \sin\varphi \cdot \frac{d}{2} \qquad (\mu = \tan\varphi) \qquad \text{(Eq.13)}$$

Where $\varphi$ = Offset angle [°]

Based on the formulas stated, the solutions of the two cases differ by a factor of $\cos\varphi$.

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# Nomenclature

| | |
|---|---|
| T&D | Torque and Drag |
| FF | Friction Factor |
| RIH | Running In Hole |
| POOH | Pulling Out Of Hole |
| ROB | Rotating Off Bottom |
| DWOB | Downhole Weight On Bit |
| DTOB | Downhole Torque On Bit |
| WOB | Weight On Bit |
| TOB | Torque On Bit |
| PU | Pick / Picking Up |
| SO | Slack / Slacking Off |
| BHA | Bottom Hole Assembly |
| MWD | Measurement While Drilling |
| PRS | P (Picking Up), R (Rotate), S (Slacking Off) |
| ROP | Rate Of Penetration |
| OpRec | Operations Recognition |
| WITS | Wellsite Information Transfer Specification |
| TaD | Torque and Drag (name of the software and OpRec rule developed) |
| OOS | Out Of Slips |
| RMT | Runs Management Tool |
| MD | Measured Depth |