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Evidences of Poor Hole-cleaning or of Wellbore Instability through Hook load Response

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Abstract

Poor hole-cleaning and wellbore instability are well-known problems during drilling operation. If they are not diagnosed in their early stage of development, they result in non-productive time (NPT). In order to reduce NPT, potential problems due to poor hole-cleaning or wellbore instability need to be revealed and preferably distinguished between them before they occur and take the correct measures to rectify the situation.

Hook load (HKL) is one of many parameters of the real time drilling data (RTDD) measured at the surface during drilling operations. In this work the RTDD were investigated closely to find the deviation of HKL from normal, and snapshots for each detected case were presented.

From 12 well studied, 26 downhole restriction cases were found. The cases were distinguished based on HKL deviation due stability of the wellbore (Abnormal HKL type 1), HKL deviation due to cleaning of the wellbore (Abnormal HKL type 2), and cases of formation related. Cases (1 to 9) were of Abnormal HKL type, cases (10 to 16) were of Abnormal HKL type 2, and cases (17 to 26) were of formation related. The ontologies for both Abnormal HKL type 1 and Abnormal HKL type 2 were also presented along with the average probabilities of the main cause.

Distinguishing the downhole restriction into restriction due to wellbore and wellbore wall is a challenging task. However, snapshots of HKL response are useful in creating data agents to detect downhole problems before it occurs or become serious.

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1. Introduction

With an increasing world demand for oil and gas, more wells have been drilled at locations which later turned out to be uneconomical. This has increased well complexity as the limit of the drilling envelope is pushed both in depth and length. Most of the wells drilled in these locations are not trouble-free (Yilmaz, 2008). They are associated with restrictions during tripping operations which results in non-productive time (NPT).Examples of restrictions are accumulated cuttings and cavings, key seat, creeping wellbore, shale swelling, ledges etc.

Drilling cost (NPT) for the oil company BP approached 4,000 days and $1 billion in 2007 (Yilmaz, 2008). Of that figure, formation-related problems account for over one third of the NPT. Many of these problems were aggregated into two cause types; wellbore instability and stuck pipe (Yilmaz, 2008). One way to reduce downtime related to poor hole-cleaning and wellbore instability is to detect potential problems before they occur and take correct measures to rectify the situation.

Hook load (HKL) is one of many parameters of the real time drilling data (RTDD) measured at the surface during drilling operations. The HKL represents the buoyed weight of the drillstring and its friction with the surroundings while moving the friction part. It is affected by many factors such as wellbore geometry, friction factors between borehole wall and drill string, cuttings concentration etc. The HKL can be used to detect restrictions in the well and distinguish between the causes of restriction by analyzing the characteristics of the anomalies in the HKL data plot. By distinguishing between the restrictions, the correct remedies may be applied quickly, and NPT due to borehole restrictions may be minimized to a certain degree (Glomstad, 2012).

By determining the type of restriction and the causes behind the restriction, the treatment of the problem become more purposeful and efficient. Different causes need different repair strategies, hence selecting the wrong repair strategy may make the situation worse instead of improve it. The goal of this work is to make it probable that two restriction types can be distinguished;

- HKL deviation caused by wellbore restrictions and
- HKL deviation caused wellbore wall restrictions

The wellbore is representing accumulation of cuttings and cavings, while the wall is represented by shale swelling, creeping wellbore and filter cake building up (latter not so probable in the overburden since it requires permeable zones, but more probable while drilling in the reservoir).

The approach to solve the challenge presented in this work will be as follows;

1 Theory behind hook load (HKL) measurement
2 Describe the factors influencing measured weight of drill string
3 Building knowledge on previous methods used to find evidences of poor hole cleaning and of wellbore instability, including building knowledge on ontology engineering

4 Consult the End of Well (EoW) report to obtain a rough overview of where the drilling crew experienced problems in focus
5 Open the RTDD and look closely at them. Looking for deviations in the HKL during tripping and reaming and especially when deviation is different from 'normal' overpull and took weight
6 Detecting failure cases in the RTDD and present them through snap shot and explanation. For each case detected in the data, a complete investigation will be built including type of condition which most probable caused the incident
7 Failure cases evaluation, including testing the cases through ontology

2. Parameters affecting Hook Load

In order to understand the response of hook load in restrictions due to poor hole-cleaning or wellbore instability, the physics on how hook load is measured is important. In this chapter factors affecting hook load during drilling, downhole restrictions and previous work on hook load response are discussed.

2.1. Definition of Hook Load

The hook load is the vertical force that pulls down on the elevator or the top-drive shaft at the bottom of the travelling equipment. It is determined by considering forces acting on drillstring attached to the hook, including the weight of the submerged string and mechanical and hydraulic friction forces. The hook load is thus sensitive to (Eric, Skadsem, & Kluge, 2015):

- Drag force due to friction at the contact points between the string and wellbore wall
- Pressure forces due to buoyancy,
- Fluid movement inside curved string section and fluid shear stress at the pipe walls.

The hook load is one of the drilling parameters which is mostly used as an indicator of downhole conditions, of mechanical friction and to estimate weight (Eric et al., 2015).

2.2. Hook load measurement

Historically hook load has been measured using the 'weight indicator'. The weight indicator operates using the signals from the deadline. The hook load *'w'* displayed by the weight indicator is assumed to be equal to number of lines between blocks, n, time the deadline tension F_{dl} (Luke & Juvkam-Wold, 1993).

$$w = F_{dl}n \qquad (1)$$

This equation does not account for the friction effect; hence no consideration is given between static and dynamic conditions (Luke & Juvkam-Wold, 1993).

The figure 1 below describes an over view of how the system of hook load measurement from tension lines is obtained.

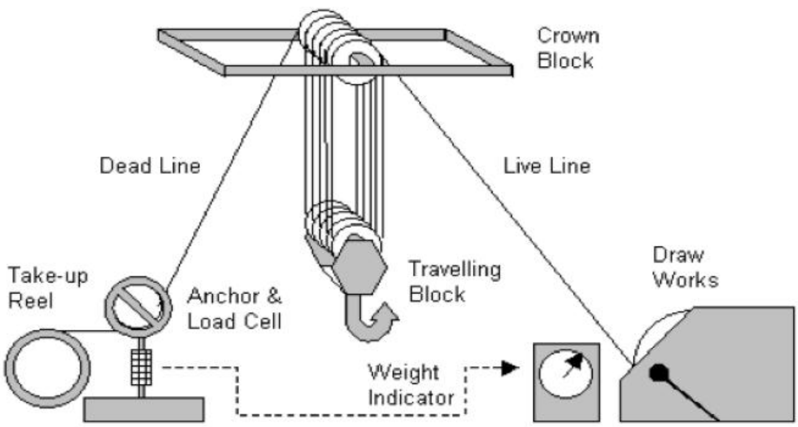

Figure 1: Measurement of hook load from weight indicator(Glomstad, 2012)

2.3. Factors affecting Hook load during drilling

There are many factors that are taken into consideration while observing the HKL trend during drilling of oil and gas well. In this section six factors affecting hook load while drilling are discussed.

(a) Buoyed Drillstring weight

When the drillstring is submerged in the drilling fluid, the weight recorded weight of the drillstring suspended by the hook depends on the densities of the drillstring and drilling fluid in the borehole. Figure 2 shows the forces acting on the drillstring in vertical well in which the drillstring is submerged. In this case two forces are acting which affects the hook load. These are gravity and buoyancy forces. Buoyance force is the upward force that exerted by fluid and it opposes the gravity force (Glomstad, 2012). The buoyant force based on Archimedes' principal which states that "Any object, wholly or partially immersed in a fluid, is buoyed a force equal to the weight of that fluid displaced by the object"(Wikipedia, 2016).

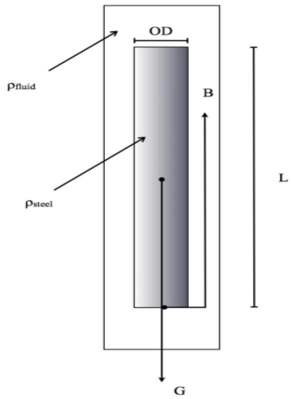

Figure 2: Submerged drillstring forces in a vertical well (Glomstad, 2012)

(b) Friction

Friction is one of the limiting factors in most of the extended reach drilling operations. Friction can be defined as the force that resists motion between two surfaces in contact. Usually the motion under consideration is the tangential motion. Tangential motion is defined as the sliding behavior between two surfaces and acts between two surfaces and acts opposite way of the relative motion(Sjøberg, 2014)
The friction force can only be found empirically. Coulomb friction is an approximate model used to calculate the force of dry friction (Glomstad, 2012)

$$F_f = \mu F_n \qquad (2)$$

The direction of coulomb friction force is in the exact opposite direction of the relative motion between the two surfaces. When the drillstring is lowered, the friction acts upwards, and when the drillstring is hoisted, the friction acts downwards (Glomstad, 2012).

(c) Side forces

These are normal forces caused by bending and tension of the drillstring. Normal forces are common in deviated due to change in azimuth and inclination to meet the target. In the deviated wells the side forces are likely to occur at drop and build up sections. Figure 4 illustrates the side forces(Kristensen, 2013)

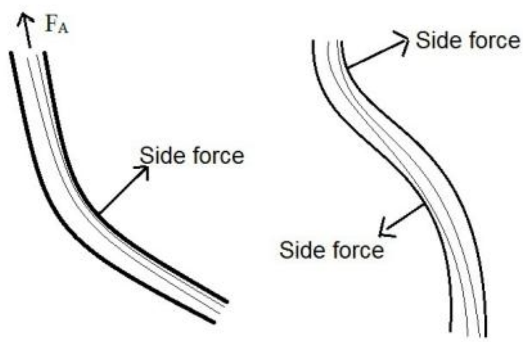

Figure 3: Side forces on drill pipe. (Kristensen, 2013)

(d) Wellbore geometry and restrictions

The structural geometry of the wellbore (dogleg, keys seat, washout) cutting and caving concentrations, and swelling shale affect the hook load measurement during drilling operation. They have direct effect to the overall friction force during tripping in or out of the wellbore. Hook load value depend on the wellpath. The normal force and weight of the drillstring are affected by wellbore inclination (Glomstad, 2012).

(e) Elastic behavior

The drillstring is made of steel, which is an elastic material (Glomstad, 2012). While tripping the drillstring experiences a compression or tension forces. The force may cause the drillstring to deform. This deformation may affect the hook load value and bit depth measurement (Sjøberg, 2014).Elastic behavior can be defined as temporary deformation. After removal of tension or compression force the object returns to its original state (Sjøberg, 2014) .

(f) Fluid drag

Fluid drag is the friction force which occurs in the well as a result of contact surface between the surface of drillstring and the fluid. When pulling the drillstring, the mud exerts an extra friction. This friction force depend on the relative motion velocity between two objects, as well and the fluid viscosity (Sjøberg, 2014).

2.4. Downhole Restrictions

Several downhole restrictions are encountered during tripping operations. These restrictions have different cause. This section will discuss the theory behind six selected type of restrictions.

2.4.1 Swelling wellbore

It is known that more than 75% of all drilled formations consists of shale increases the risk of unstable wellbore due to shale swelling, hence before drilling and circulating through these formations a carefully planning and evaluation is need. However, shale instability is still the reason for more than 70% of all wellbore problems. Reaction between shale and drilling fluid may results to a chemical unstable wellbore which may cause the shale to swell and weaken. If the remedial actions are not taken, the formation can collapse or the shale may become plastically and flow into the formation (Agasøster, 2013). The figure below shows a situation where swelling formation is causing restriction to the drillstring

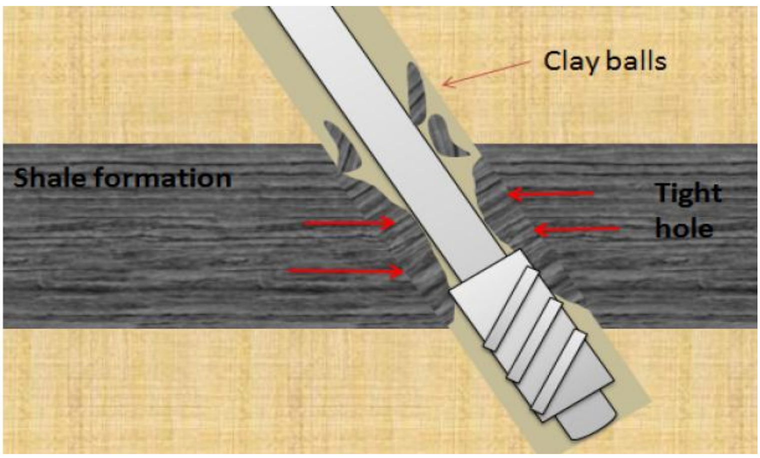

Figure 4: Swelling wellbore (Agasøster, 2013)

2.4.2 Creeping wellbore

The creeping wellbore results in a decrease in hole diameter due to mobile or plastic formation causing “tight hole”. These formations are slowly moving into the wellbore and if the wellbore stays open for a sufficient period of time the drillstring may meet restrictions during tripping, hence the string may not be able to pass anymore (Bjerke, 2013). The common examples of creeping formations are halite and Claystone which are able to deform under stress (Skalle, 2014).

When creeping wellbore occurs the hook load signal is expected give a sudden overpull/ took weight. The drillstring should be free to move in one direction, provided that the creeping formation does not squeeze around the drillstring. During tripping in the drillstring is not able to pass the creeping point without drilling through it again. One of the symptoms for creeping wellbore can be an increasing in mud salinity due to presence of halite (Bjerke, 2013).

2.4.3 Differential Pressure Pipe Sticking

This is common case in permeable formation due to the formation of thick mud-cake around the part of static drillstring. The string cannot move up or down. It due poor mud properties which results to higher pressure in wellbore than in the formation and thick mud cake (Bjerke, 2013).

2.4.4 Cuttings accumulation

Poor hole cleaning result to overloading of cuttings in the annulus. Hole cleaning is an important part of the drilling process and involves removal of all drilled out materials. Even though a lot of time is spent on hole cleaning, both during drilling operation and continuously on research of how to increase the cleaning efficiency, it is still one of the most frequent problem during drilling(Agasøster, 2013)

Until the beginning of the 1980s, most wells to be drilled were vertical. Today, vertical wells are mostly drilled for exploration while horizontal wells are preferred due to the economic advantage(Agasøster, 2013).

Cutting beds is challenge in deviated well since cuttings behave differently depending on well angle (K&M-Technology-Group, 2011). It is a problem arising in deviated well due to the fact that the settling distance is reduced rapidly compared to the vertical wells. In deviated wells the vertical velocity is reduced and hence ability of drilling fluid to keep cuttings in suspension decreases. In vertical wells cuttings can remain suspended in drilling fluid even when the circulation stops, but in deviated wells cuttings can settle to the bottom of the borehole (Glomstad, 2012). Figure 5 depicts the concentrations of cuttings in vertical and deviated well sections.

Figure 5: Cuttings in high angle well sections (K&M-Technology-Group, 2011)

2.4.5 Restriction due to washout

Borehole washout is an enlargement in the openhole section created by either borehole breakout or by hydraulically or mechanically erosion of weak formation. Wellbore washouts are especially common when drilling shallow shale formations. Shale reacts easily with water in the drilling mud, swells and breaks off into the wellbore (Agasøster, 2013).When there is washout in the wellbore, it is filled with cuttings. After long periods of circulation during drilling a hydrodynamic equilibrium will cause a thicker bed in the washout. When the BHA is shoveling large amount of cuttings into the normal part of borehole, *overpull* is experienced which indicated as an increase in hook load value (Skalle, 2014). Figure 6 illustrate the cutting bed in the washout.

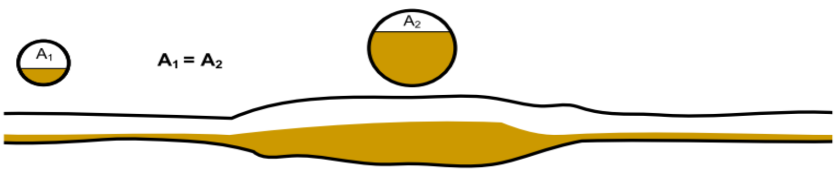

Figure 6: Cuttings accumulation in washout of the borehole(Skalle, 2014)

2.5. Previous published work on evaluating RTDD

The goal of this work is to make it probable that two restriction types can be distinguished: Hook load deviation caused by wellbore restrictions and hook load deviation caused by wall restrictions.

There are some previous works used to identify hook load response due to different downhole restrictions.(Cordoso Jr et al., 1995) provided a field diagnosis method for detecting problems during tripping operations in horizontal and deviated wells using Two stage Type curve matching. An alert hook load expert system followed by a pseudo friction factor ' signature analysis'. Different standard curves are presented. The curves are plotted based on the hook load data analysis (Cordoso Jr et al., 1995)

(a) Tripping Type Curve

Figure 7 shows the tripping out curve for one section of the pipe. The following effects take place during tripping out of the pipe (Cordoso Jr et al., 1995):

- The accelerations and deceleration predominated at the beginning and end part of the pulled out pipe section
- Within the center part, the values oscillate around an average value. The value is a function of true borehole friction factor and any factor that can cause hook load to increase. If this value is between the hook load calculated for $f_b = 0$ and $f_b = f_{bn}$,f_{bn} is usually within 0.2 and 0.4, no problem are assumed to have occurred, hook load within this range are referred to here as normal. If average hook loads are above this normal hook load

range, pseudo friction factor analysis is performed for the entire trip out.

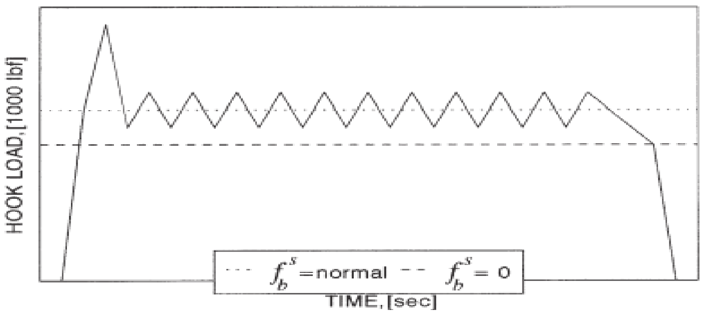

Figure 7: Tripping type curve (Cordoso Jr et al., 1995)

(b) Ledge Type Curve

From Figure 8 two disturbances can be seen in the central part of the curve type. One disturbance occurs at about 30% of the section trip time and the other at about 70%. Theses disturbances are caused by the tool joint or any part of a drillstring with shoulder on it (e.g. stabilizers) hitting the ledged (Cordoso Jr et al., 1995).

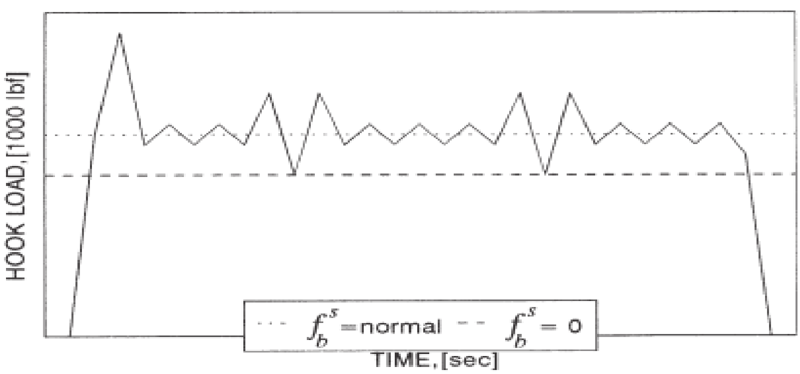

Figure 8: Ledge Type Curve (Cordoso Jr, Maidla, & Idagawa, 1995)

(c) Borehole Closure Type Curve

Figure 9 shows the hook load response for borehole closure. Borehole closure is a common problem in field. During tripping operation in borehole closure section operation is followed by succession of pipe stretching and, quick sudden movement, high acceleration and deceleration , and further stretching, throughout the entire section being pulled out, thus indicating much difficulty in moving the pipe (Cordoso Jr et al., 1995).

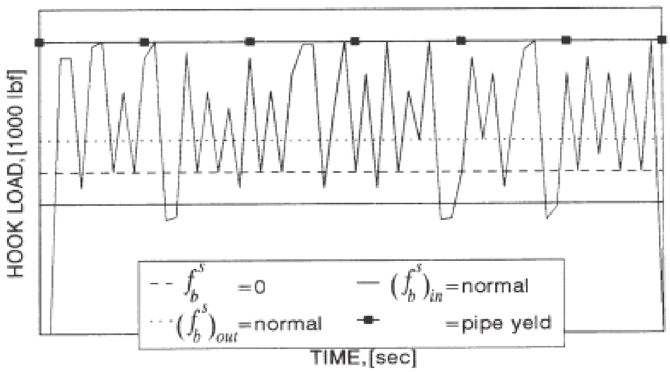

Figure 9: Borehole Closure Type Curve (Cordoso Jr et al., 1995)

(d) Differential Sticking Type Curve

Figure 10 shows hook load trend for differential sticking in one pipe section. When the incremental in axial force exceeds the differential sticking drag force, the pipe is released and normal patterns takes place. This occurs because differential sticking does not happen instantaneously but rather is a time dependent static phenomena that takes place between the pipe and mud cake surface (due to the mud cake thickness) (Cordoso Jr et al., 1995).

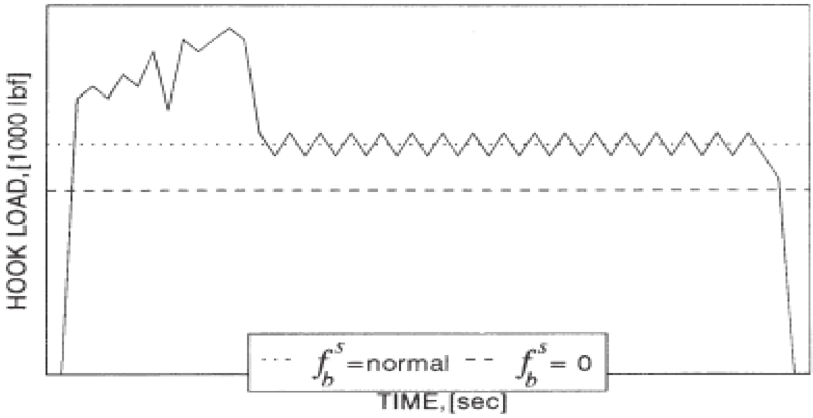

Figure 10: Differential Sticking Type Curve (Cordoso Jr et al., 1995)

2.6. Typical normal and abnormal Hook Load

This chapter is an introduction to chapter 5.In order to find the failure cases related to poor hole cleaning or wellbore instability, a deeper understanding of the HKL response during tripping and reaming operations is needed. In this chapter, a general introduction of hook load response for normal and abnormal conditions is presented using the snapshots from the wellbore 34/10-48A.

Drilling a well consists of different activities such drilling, circulating, tripping in and out, and reaming (Shokouhi, Skalle, Aamodt, & Sørmo, 2009). Most of the wellbore instability and poor hole-cleaning failure cases occur during tripping operation. In this thesis, the focus will be on tripping and reaming operations to find the evidences of poor hole-cleaning or of wellbore instability through HKL response.

Table 1 describes definition of the most frequent used drilling activities. Where B= weight of travelling block, WODS= weight of drillstring. Definitions of symbols are ↑ moving up ↓ moving down Y active parameter X inactive parameter(Shokouhi et al., 2009)

Table 1: Definition of the most frequently used drilling activities(Shokouhi et al., 2009)

Parameter / Activity	Rotation	Pumping	Block movement	Hook load
Drilling	Y	Y	↓	WODS-WOB
Tripping in	X	X	↓	WODS-friction
Tripping out	X	X	↑	WODS+friction
Reaming	Y	Y	↓	WODS-(WOB+friction)
Backreaming	Y	Y	↑	WODS+(WOB+friction)
Connection	X	Either	X	B
Circulating	X	Y	X	WODS

The following assumptions are taken into consideration when creating failure cases

- Hook load deviation is associated with downhole restrictions
- Downhole restrictions occur during tripping in or out of hole and reaming operations

2.6.1 Normal Hook load during tripping

During tripping, the RTDD presents the hook load along with the block position. A drillstring connection is done at approximately every 30 meters (90 feet). Each of these sections of drillstring is referred to as stands. When a stand is made up and attached to a new one, it is referred to a connection (Sjøberg, 2014). Normal hook load can be easily recognized in the plot of hook load vs. depth compared to the predicted trend (calculated) (Kucs, Spoerker, Thonhauser, & Zoellner, 2008).

Figure 11 represents the activity of tripping-out one stand through well 48A, section 8 ½”, it represents smooth, normal hook load behavior. Hook load behavior can be defined as normal when there are no high peaks in the hook load signature. The tripping out speed is 3 min/stand.

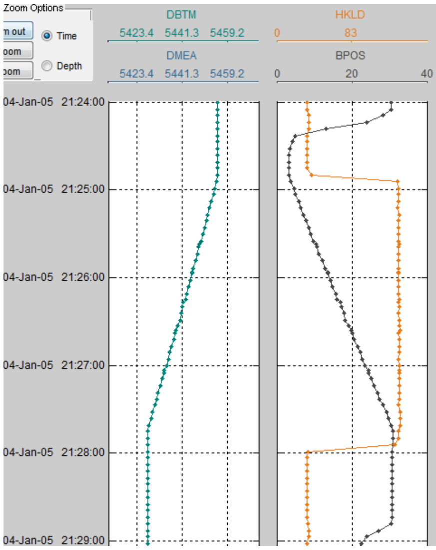

Figure 11: Normal Hook load behavior during tripping out at 3min/stand one stand between 5492 m to 5423 m in wellbore 34/10-48A, 8 ½" section (Data from Statoil via Verdande Technology)

2.6.2 Abnormal hook load during tripping

Any deviation in the normal hook load value is considered as abnormal hook load. In many cases, it is marked as overpull or took weight. Overpull is the addition hook load to the normal value measured when the drillstring is moving; took weight is the reduced weight of the drillstring when the drillstring is moving down (Belaskie, McCann, & Leshikar, 1994).

Figure 12 represents the activity of tripping in one stand through a well 48A with 8 1/2" RSSS BHA from 5100 m to 5970 m at 2min/stand took the 20-ton weight. Hook load behavior can be defined as abnormal when there are high peaks in the hook load signature.

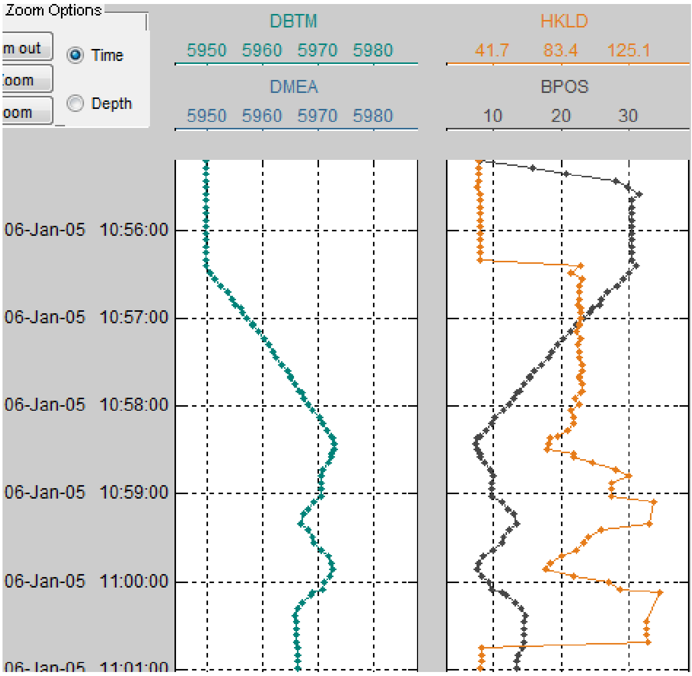

Figure 12: Abnormal hook load behavior during RIH at 2 min/stand at 5970 m in wellbore 34/10-48A, 8 ½" section (Data from Statoil via Verdande Technology)

3. Ontology engineering

The easy oil and/or gas are gone. Exploration, drilling, and production of the remaining hydrocarbons challenge the existing technology, therefore the industry needs to develop more advanced solutions to the current challenges (Kristensen, 2013).

A majority of the remaining hydrocarbons in the world are located on the continental shelves. Accessing these reserves (offshore drilling operations) is very expensive and numbers of wells need to be as low as possible (Skalle, Aamodt, & Gundersen, 2013b). As the oil and gas wells grow both in depth and complexity, and the rig rates are also becoming high, the need for reduction of operational downtime; Non-Productive Time (NPT) is high (Kristensen, 2013).

The main challenge has been how to accurately understand and determine the exact root cause of the failure and take appropriate counter measures to avoid its reoccurrence so as to reduce NPT (Skalle et al., 2013a). Ontology engineering is used in determining the main cause of failure during drilling operations.

Ontology is a term used in philosophy, encompassing the study of "what is". The use of ontology in information technology and engineering domain is more recent development, which has replaced and enhanced terms like knowledge model, data model, and term-catalog. The ontology may be very simple containing only taxonomy of domain terms linked by subclasses. All ontologies make some assumptions about the domain they present (Skalle et al., 2013a).

The purpose of the ontology is to serve as knowledge model for model-based reasoning (MBR) to assist the cased based reasoning (CBR) process. The ontology can be viewed by semantic, where each node in the network corresponds to a concept in the knowledge model and each link corresponds to a relation between concepts (Skalle et al., 2013b). Example of ontology describing subclass failure state during drilling process is shown in figure below

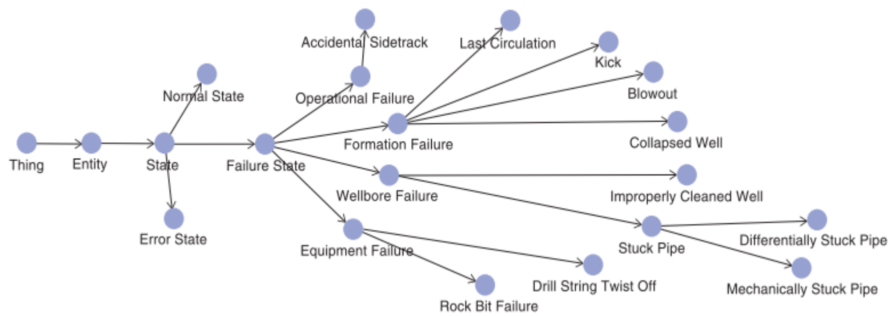

Figure 13: Example of subclass Failure State, structured into subclasses of concepts interconnected through relations has subclasses (Skalle, Aamodt, & Gundersen, 2013a)

Ontology engineering is used to determine the main cause of downhole restrictions discussed in chapter 2. These downhole restrictions are the caused by poor hole-cleaning or wellbore instability. In chapter 4, the ontologies of hook load cases discussed in chapter 5 are presented.

4. The ontology of Hook load cases in focus

This chapter presents ontologies of the hook load cases found in chapter 5. Before presenting the ontologies practical direction on how to build ontology is discussed.

4.1. Practical direction of how to build ontology

This section describes on how to build ontologies in oil and gas well drilling engineering. This direction of how to build ontology is according to Pål Skalle's class notes titled ***Best Practice-ontology***.(Skalle, 2015)

a) Introductory ontology rules

- First name of a concept should reflect the main word / its meaning; i.e. Bit Balled, not Balled Bit
- Most concepts have sub class (whenever you can say: B is an A) or instances (whenever you can say: B is a concrete example of A)
- Sub classes of A should be placed logically in a hierarchy and cover all possible (but relevant) types of A
- A concept name must be as short as possible, but still precise enough to be unique
- A concept must be defined in the description slot of a concept (concept frame)
- Noun (Entity); each word starts with capital letter
- Verb (Relation) is written purely in small letters

b) Concept type

There are five groups of entities. These are as follows

(err)= error

(f)= failure

(s)= symptoms based on one, two or more

(ss) = static symptoms

(i) = internal parameters.

Symptoms are data agents, detectable in the real time data. Errors and failure are also internal entities. They are intended to, as an end –result of this research project, either be predicted or explained

Static symptoms (ss) are known before the program is activated. They are read from the EoW reports or drilling plan.

Internal (i), error (err) and failure (f) concepts are non-observable parameter. If possible make into symptoms at a later stage, through future improvements of metering/ logging technology.

Symptoms do not need to occur exactly at the time of the incident, but rather within a time span of say 1hour. Many symptoms will be indicative of the process for a while.

c) Relations between concepts

There are two main relations here: Structural and cause-**effectual**.

- Structural: The basic structural relations are; has subclass, has instance, has part
- Causal: To obtain consistency and to simplify the building process, only 5 strength levels are used: 02, 04, 06, 08 and 10, meaning 20, 40, 60, 80 and 100 % probability for that relation to occur. See table 2 for more clarification
- Parameters are assumed to have already taken place when the relation strength is expressed; a priory relations. Still, it is better to think of the word 'causes' as 'affects, enables, influences'
- Case relations: case relation 'has case' is need. If more case relation types is needed it will be will adjust according to the need

d) Procedure of building the ontology

- Develop relationships stepwise. In step1 through physical description whenever suitable formal concepts are not at hand. Make acceptable, but only obvious concepts in step 2
- Start by focusing on the why (caused by, the from-concept). Reveal the physics behind the relationship. Implications (causes, the to-concept) can be added later when the causes are understood
- Try to find directly related concepts only, not indirect related. Too many duplicating relations to and from will be chaotic for the ontology builder and for the ontology itself

- Make short explanation behind suggested to-concepts or from-concept. Explain it for your own benefit, but also for a colleague, if not obvious
- Include logical operators like conditional (IF), simultaneously occurring (AND), and alternatively occurring (OR) relations in the comment field, i.e. If Well Deep. Relation strength will then vary accordingly
- Include typically 1 2 or 3 strength levels; medium, high, very high. Relation strength vary accordingly
- Check reversed strength (in separate column). Often identical, but far from always

***Table 2:** Assumed causal relation and strength for ontology*

Causal relation	Strength (%)
Causes always	100
Causes	80
Leads to	60
Causes sometimes	40
Causes occasionally	20

4.2. Ontologies of Hook load cases

In these section ontologies of HKL cases from wellbore 34/10-48A (abnormal HKL type 1) and 34/10-C-47 (abnormal HKL type 2) are presented.

Table 3: Ontology of cases 1 to 9 for Abnormal HKL type 1

A	B	C	D	E
Available Drilling process parameter		OFU		SI
Fm Special Expected	2 options: Yes or No;Yes Cod Fm Unstable	No		
Fm Boundary Expected	2 options: Yes or No;Yes Cod Fm Unstable	No		
Fm Fault Expected	2 options: Yes or No;Yes Cod Fm Unstable	No		
Fm Permeable Expected	2 options: Yes or No;Yes Cod Fm Unstable	No		
Errosion Wellbore Factor				1.1
Losses Expected	2 options: Yes or No --> Yes; in Tare	Yes		
MD Build/Dropp Upper	Its approximate mid point. Upper is normally inside csg			**5350**
MD Build/Dropp Lower	Its approximate mid point. Could well be in the openhole. If only one build/drop then upper is also the lowest!			**5350**
MD Casing Shoe	The Last			1600
MD Water Depth				**216.9**
MD Well				**6221**
Mud Type	2 options: WBM or OBM	OBM		
Mud Water Activity				**0.9**
Mud Weight		10	ppg	**1.59**
Mud YP		18	lb/100 f	8.5
Shallow Gas Expected	2 options: Yes or No	No		
TVD. Well				**2870**
Well Inclination	Take the average of the last hudreds of meter	**89.25**		
static symptoms which may appear during a failure incident				
Build/Drop Section Inside Csg(ss)	When (MD.Csg.shoe- MD.Build/Drop upper) >0	E11-E9	1	
Build/Drop Section Inside openhole (ss)	When (MD.Csg.shoe- MD.Build/Drop upper) <0	E11-E10	0	
Fm Special Expected (ss)	Here 1= yes	C3	0	
Fm Boundary Expected (ss)	Here 1= yes	C4	0	
Fm Fault Expected(ss)	Here 1= yes	C5	0	
Fm Permeable Expected(ss)	Here 1= yes	C6	0	
Losses Expected(ss)	Here 1= yes , known before drilling	C8		
Mud Water Activity High(ss)	When Aw > 0.8 - 0.85 - 0.9	E15	3	
Mud Water Activity low(ss)	When Aw < 0.8 - 0.7 - 0.6	E15	0	
Mud Weight High(ss)	When MW > 1.5 - 1,65 - 1,8 kg/l	E16	0	
Mud Weighting Material is Basrite(ss)	When MW.Material = Barite		0	
Mud YP High(ss)	When Mud.YP > 15 - 25 - 35 Pa	E17	1	
OBM(ss)	Need to know typ of mud in use (OBM or not)	C14	1	
Shallow Gas Expected (ss)	Challenging to drill through. Avoid by moving the rig	C18	0	
Water Depth High(ss)	When Water.Depth > 300 - 500 - 700 m	E12	3	
WBM(ss)	When Mud:Type = WBM	C14	1	
Well Depth High (ss)	Well TVD > 2 - 3 - 4 km	E19	3	
Well Depth Shallow (ss)	When Well.TVD < 2 - 1,5 - 1 km	E19	0	
Well Inclination Medium (ss)	When Well Inclination between 30 and 60 degrees	C20	0	
Well Inclianation High(ss)	When Well Incl. > 60 degrees. See WellPlan /EoW	C20	1	
Well Incliantion low (ss)	When Well Inclination < 30 degrees	C20	0	
well Length High(ss)	Measured Well Length > 3 - 4 - 5 kmMD	E13	3	
Well Openhole Long(ss)	If (MD.Wl-MD.Csg.Shu) > 0.4 - 0.75 - 1 kmMD	E13-E11	3	

Table 4: causal relation of cases 1 to 9 for Abnormal HKL type 1

Observation	Path strength	Explanation strength	Target error	Probability
Pack off	1	3.8	Accumulated cuttings	0.45
overpull	1			
Took weight	1			
reaming	0.8			
Pack off	0.8	4.6	Swelling clay	0.55
Took weight	0.8			
very long open hole	0.8			
Backreaming	0.8			
Reaming down	0.8			
Mud Water Activity high	0.6			
Total	8.4			1.00

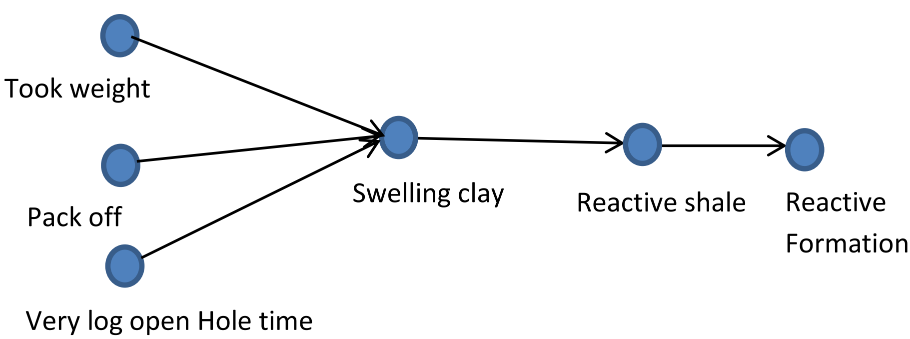

Figure 14: Knowledge model for Abnormal HKL type 1

Table 5: Ontology of cases 10 to 16 for HKL type 1

A	B	C	D	E
Available Drilling process parameter		OFU		SI
Fm Special Expected	2 options: Yes or No;Yes Cod Fm Unstable	No		
Fm Boundary Expected	2 options: Yes or No;Yes Cod Fm Unstable	No		
Fm Fault Expected	2 options: Yes or No;Yes Cod Fm Unstable	No		
Fm Permeable Expected	2 options: Yes or No;Yes Cod Fm Unstable	No		
Errosion Wellbore Factor				1.1
Losses Expected	2 options: Yes or No --> Yes; in Tare	Yes		
MD Build/Dropp Upper	Its approximate mid point. Upper is normally inside csg			**1523.9**
MD Build/Dropp Lower	Its approximate mid point. Could well be in the openhole. If only one build/drop then upper is also the lowest!			**1523.9**
MD Casing Shoe	The Last			2359.75
MD Water Depth				**216.9**
MD Well				**4399**
Mud Type	2 options: WBM or OBM	WBM		
Mud Water Activity				**0.9**
Mud Weight		10	ppg	**1.59**
Mud YP		18	lb/100 f	8.5
Shallow Gas Expected	2 options: Yes or No	No		
TVD. Well				
Well Inclination	Take the average of the last hudreds of meter	**72.56**		
static symptoms which may appear during a failure incident				
Build/Drop Section Inside Csg(ss)	When (MD.Csg.shoe- MD.Build/Drop upper) >0	E11-E9	1	
Build/Drop Section Inside openhole (ss)	When (MD.Csg.shoe- MD.Build/Drop upper) <0	E11-E10	0	
Fm Special Expected (ss)	Here 1= yes	C3	0	
Fm Boundary Expected (ss)	Here 1= yes	C4	0	
Fm Fault Expected(ss)	Here 1= yes	C5	0	
Fm Permeable Expected(ss)	Here 1= yes	C6	0	
Losses Expected(ss)	Here 1= yes , known before drilling	C8		
Mud Water Activity High(ss)	When Aw > 0.8 - 0.85 - 0.9	E15	3	
Mud Water Activity low(ss)	When Aw < 0.8 - 0.7 - 0.6	E15	0	
Mud Weight High(ss)	When MW > 1.5 - 1,65 - 1,8 kg/l	E16	0	
Mud Weighting Material is Basrite(ss)	When MW.Material = Barite		1	
Mud YP High(ss)	When Mud.YP > 15 - 25 - 35 Pa	E17	1	
WBM(ss)	Need to know typ of mud in use (OBM or not)	C14	1	
Shallow Gas Expected (ss)	Challenging to drill through. Avoid by moving the rig	C18	0	
Water Depth High(ss)	When Water.Depth > 300 - 500 - 700 m	E12	3	
WBM(ss)	When Mud:Type = WBM	C14	1	
Well Depth High (ss)	Well TVD > 2 - 3 - 4 km	E19	1	
Well Depth Shallow (ss)	When Well.TVD < 2 - 1,5 - 1 km	E19	0	
Well Inclination Medium (ss)	When Well Inclination between 30 and 60 degrees	C20	0	
Well Inclianation High(ss)	When Well Incl. > 60 degrees. See WellPlan /EoW	C20	1	
Well Incliantion low (ss)	When Well Inclination < 30 degrees	C20	0	
well Length High(ss)	Measured Well Length > 3 - 4 - 5 kmMD	E13	3	
Well Openhole Long(ss)	If (MD.Wl-MD.Csg.Shu) > 0.4 - 0.75 - 1 kmMD	E13-E11	3	

Table 6: Causal relation of cases 10 to 16 for Abnormal HKL type 2

Observation	Path strength	Explanation strength	Target error	Probability
Pack off	1	3	Accumulated cuttings	0.65
overpull	1			
Took weight	1			
Pack off	0.8	1.6	Swelling clay	0.35
Took weight	0.8			
Total	4.6			1.00

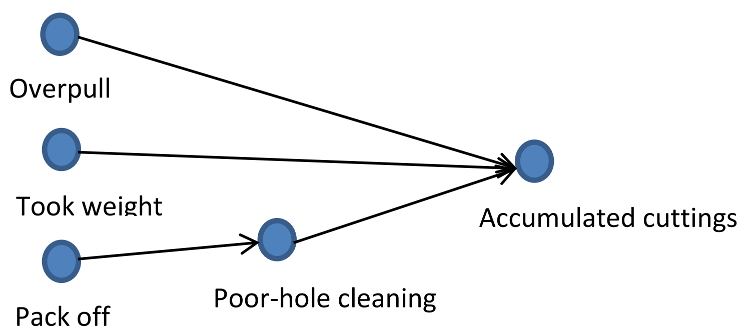

Figure 15: Knowledge model for Abnormal HKL type 2

5. Hook load cases

This chapter presents several downhole failure cases through snapshots and explanation. The failure cases were obtained from the Statoil and the AGR database sources. From Statoil source, the cases were developed by using the End of Well reports and RTDD. The Matlab Script created by Verdande Technology helped to view well data. In the AGR database, only the End of Well reports and depth based variables were available. Cases from AGR were developed using the information found in the EoW reports only.

5.1. Case template

In order to present the cases the following format content was taken into consideration:

1. Case Number and Name
    - Case type

    Three types are taken into consideration, which are:
    - Wellbore issues like cleaning dominated (cleaning of the wellbore). This type is due to cuttings and cavings accumulation, poor hole geometry (side force & dogleg) etc.
    - Wellbore wall issues dominated (stability of the wellbore wall). The wall responded to shale swelling, creeping formation, filter cake etc.
    - Combination of both (actually unknown)
2. Picture of the incident
3. Place of occurrence: e.g. well Rig (iQx)

4. Time of occurrence : e.g. 21:05, 06.07.2007
5. Row of events. This is important for ontology in previous chapter 4.

In order to create the row of events, the incident must be search several hours before the time of occurrence. The row of events can be summarized like shown table 7.

Table 7: Row of events

Time	Observation	Formal concept
20:15	Small restriction	Overpull
20:32	Had to perform wiper trip	Reaming
20:49	Small loss observed	Losses seepage

6. Static parameters

   These are parameters known before the drilling process is activated. Static parameters are used to calculate the static symptoms. Examples of static parameters are as follows:

   - Bit Type
   - Bit Size
   - Bit Teeth Length
   - Erosion Wellbore Factor
   - MD Water Depth
   - MD Well

Symptoms (s) are data agents, detectable in the real time data. Static symptoms (ss) are known before the drilling process is activated. Examples of static symptoms (ss) are as follows:

- Fm. Special Expected (ss)
- Fm. Boundary Expected (ss)
- Fm. Permeable Expected (ss)
- Losses Expected (ss)
- Mud Water Activity High (ss)
- Mud Water Activity Low (ss)
- Mud Weight High (ss)
- Mud Weight Material is Barite (ss)
- Mud YP High (ss)
- OBM (ss)
- Water Depth High (ss)
- WBM(ss)
- Well Depth High (ss)
- Well Depth Shallow (ss)
- Well inclination Medium (ss)
- Well inclination High High(ss)

5.2. The data sources

In order to find evidences of poor hole-cleaning or of wellbore instability data from Statoil and AGR database were taken into consideration.

(a) Statoil

The data used in this work were obtained from Statoil. These were the data for drilling, and completion of wellbores 34/10-C-47 and 34/10- 48A located in Gulfaks C field in the North Sea, Norway. The data consist of EoW reports for both wellbore 47C and 48A together with the historical real time drilling data (RTDD). Verdande Technology created Matlab scripts to view RTDD. By reading the EoW reports, it was possible to find the failure incident reported during drilling, and completion of a well. Then, the RTDD stored in Matlab script were used to view the incidents reported in EoW and present snapshot for each incident.

(b) AGR

AGR in collaboration with subsurface professionals have developed iQx^{TM} well data management and analysis software. The software stored wide ranged information of approximately 6,000 wells in Norwegian Continental Shelf, such as geological information, surface logging, wireline logging etc. (AGR, 2016) . From EoW reports of these wells, the failure cases were identified and supported with the arguments as to why they are considered to be evidences of poor hole cleaning or of wellbore instability.

5.3. Typical normal and abnormal Hook load

This section presents cases for normal (figure 16), and abnormal hook load (figure 17) to give the overview of the hook load cases in focus.

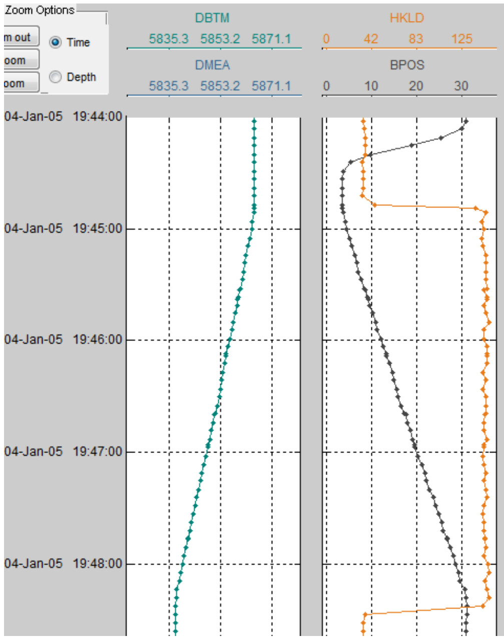

Figure 16: Normal hook load for one stand during POOH from 5976 m to 5104 m with pulling speed of 3min/stand in wellbore 34/10-48A, 8 ½" section. The hook load is more or less constant during tripping this stand (Data from Statoil via Verdande Technology).

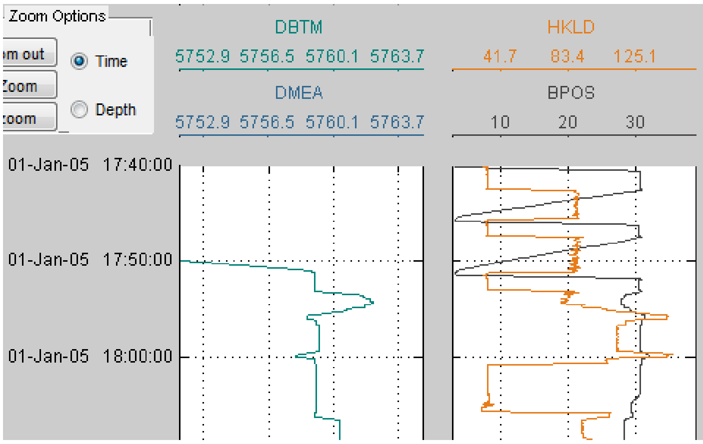

Figure 17: Hook load is abnormal; Took approximately 10 ton weight at 5760 m during RIH with 8 1/2" drilling assay on 6 5/8" DP from 5595 m to 5760 running speed 2-3 min/stand in wellbore 34/10-48A, 8 ½" section. The Took Weight is seen at 17:54, but already indicated at 17:48 (Data from Statoil via Verdande Technology).

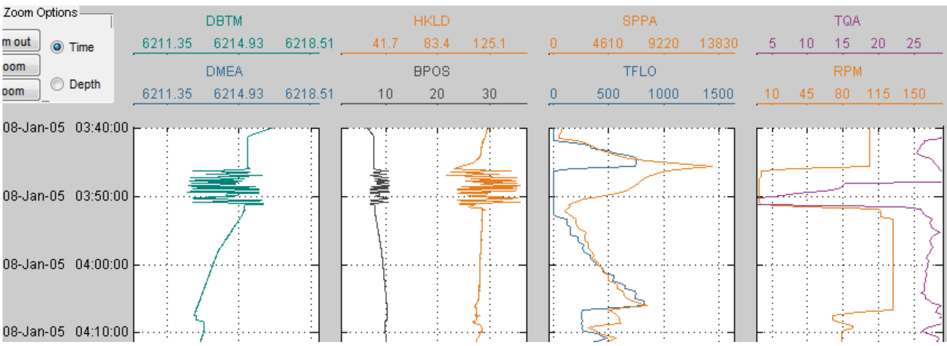

Figure 18: Abnormal, Erratic Hook Load is seen at 03:46. Pack offs during reaming back from 6214 m to 6199 m in wellbore 34/10-48A, 8 ½" section. Pack off is supported by suddenly increase in standpipe pressure at 03:45 (Data from Statoil via Verdande Technology).

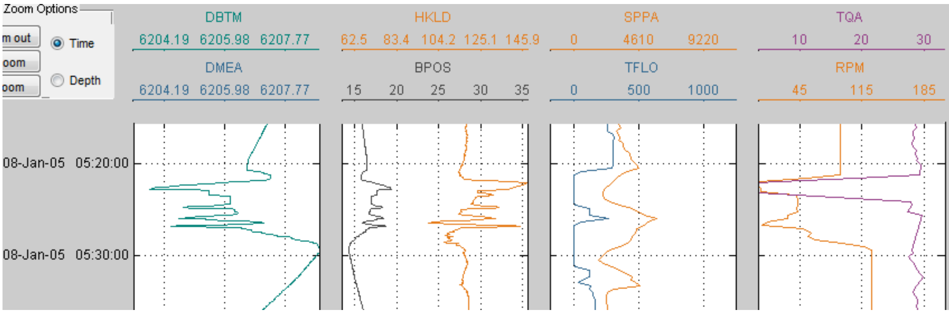

Figure 19: Another type of abnormal Hook Load is seen here; fluctuating as the drill string is moved up and down. Both in Figure 18 and 19 the drill pipe is more or less stuck. Pack off during reaming back from 6214 m to 6199 m (Data from Statoil via Verdande Technology).

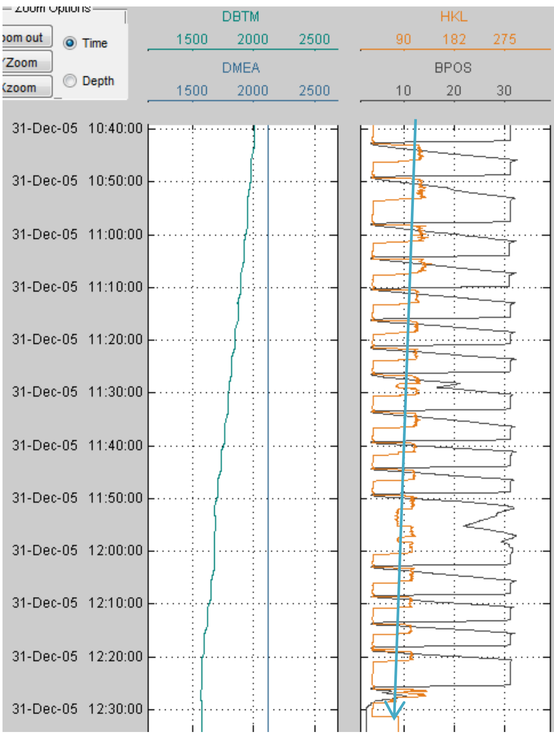

Figure 20: Here erratic HKL, Took Weight and Overpull are seen during tripping out of hole at 1563 m in 34/10-C-47, 17 ½" section. HKL decreases (blue arrow) as the string is getting shorter during pulling out (Data from Statoil via Verdande Technology).

5.4. The goal of the cases

The only goal of this task is to make it possible that the following scenarios can be distinguished:

- HKL deviation caused by wellbore restriction
- HKL deviation caused by wellbore wall restriction

The wellbore is representing accumulation of cuttings and cavings while the wall is represented by shale swelling, creeping wellbore and filters cake building up (latter not so probable since it requires permeable zones). This can, of course, happen while drilling in the reservoir.

This means that the EoW report must be consulted together with the process seen in the RTDD. For each case detected in the data, a complete investigation will be built up and conclude with which type of condition could be causing the HKL response (it could be both)

From the AGR database, cases will be formulated after reading the EoW reports for different wellbores. The arguments to support the cases will be given out.

5.5. Explanation of choice of data

In order to detect the failure cases using RTDD the following information is need:

- End of well report
- Real time drilling data

EoW report consists of field information which provides important aid in detecting failure cases related to poor hole cleaning or to wellbore instability. From EoW report the necessary data used to study the hook load responses are found. These data are like directional data, geology data, BHA & Bit data, and Drilling fluid data.

(a) Directional data

Directional data plays most important role in determining which type of restrictions is causing the downhole problem. It works best in determining whether downhole restriction is due to cutting accumulation or not. Normally cuttings start to settle at an inclination of 35° not less than that. Also in high angle wells like horizontal wells; cutting accumulation is always the case. Dogleg of the well also is important in detecting downhole restrictions like key seat. High dogleg can result into key seat which is likely to prevent the BHA of drilling string during tripping out. The dogleg is normally considered to be high if it is 3°/30 m or more (Bjerke, 2013)

(b) Geology data

Geological field information plays a great role in determining what type restriction is causing poor hole cleaning or wellbore instability. For example, the tight formation may results into the tight hole and is mostly found in swelling shales. Swelling shale results into swelling wellbores which are the form of wellbore instability. Limestone is known to be the cause of ledges due to formation of limestone stringers (hard formation).limestone can also cause bit deflection when the formation has dip angle, or ledges could be formed due to washout in the surrounding formations (Bjerke, 2013)

(c) BHA and Bit data

The BHA of the drillstring consist components with large diameter including the bit and the stabilizers as the major parts. The large diameter components are like to get stuck when passing the downhole restrictions. It is important to know the length of the BHA in order to know what area of the well the restriction most likely within. Also, it could be helpful to know the length from the bit to the different stabilizers to connect overpulls with ledges that present higher up than the bit depth. The EoW report also includes wear data on bit and stabilizer after a run (Bjerke, 2013)

(d) Drilling fluid data

The EoW report contains information about the drilling fluid. This information is useful in determining the downhole problems. When looking at the return fluid flow and amount of cutting received at the shale shaker it is possible to determine if the cuttings have settled downhole or if there is caving accumulations.

5.6. Reveal symptoms and data for the cases

Table 8: Planning of the wellbore 34/10-48A

interval	5120.0 m MD to 6221.0 m MD
Casing	N/A
Section length	Build from 70° to 103°, hold at 103° drop to 81° to TVD
Inclination	Turn from 78° to352 °
Azimuthal	1.57-1.61 sg versavert OBM

Table 9: Symptoms observed from wellbore 34/10-48A

mMD	Swelling material	Inclination (°)	Cases
5600-5800	Claystone	86-96°	• 5757 m took weight 6 ton • 5764 m took weight 14 ton • 5752-5755 m pack off tendencies
5800-6000	Claystone	82-86°	• 5970-tight hole, pack off • 5971 m pack off • 5972 m pack off
6000-6200	Claystone	82-85°	• 6144 m took weight • 6160 m pack off • 6170 m pack off
6200-6400	Claystone	81°	• 6211 m pack off • 6214 m pack off

5.7. The Cases

A Case is here defined as a specific situation that is occurring or has occurred before. It consists of parameter data and other information presented in an appropriate case structure. The set of cases contained in the system is called its case base. The case consists of three separate parts (Skalle et al., 2013b):

- circumstance information and gained experience
- explanation of why the situation arose and how it was handled and
- the outcome of the action taken

Table 10: Overview of the cases

Type Case	Number of Cases	Failure	Average Probability of the main cause (%)
Stability of wellbore wall	9	Abnormal HKL type 1	**55**
Cleaning of the wellbore	7	Abnormal HKL type 2	**65**
Other (uncertainty)	10	AGR database cases **(2 Cases)** – cleaning of the wellbore **(8 Cases) –** stability of wellbore wall	**N/A**

5.7.1 Cases from wellbore 34/10-48A

In this section 9 hook load cases were presented through snapshots. The cases were obtained from the data given by Statoil via Verdande Technology. The cases were developed by consulting the end of End of Well report for wellbore 34/10 48A and opening RTDD through Matlab script for viewing well data created by Verdande Technology.

Description of revealed Cases

Data source: Statoil

Failure Type: Abnormal HKL type 1

Place of occurrence: Wellbore 34/10-48A, 8 ½" section in Gulfaks field

During drilling in the 8 ½" section in 34/10-48A hard and soft zones were encountered. During drilling of these hard formations, the extreme slow rate of penetration (ROP) and occasionally high stick-slip were experienced. *Tripping out of hole went without problems*, but when *tripping in* the hole created several problems and finally at 6221 m after a round trip it was not possible to reach bottom due to hole condition causing pack offs. Circulation was established but each occasion when attempt was made to move the string up and down without rotation then the string packed off (Saltnes & Gundersen, 2006)

What could be the cause of several pack-offs in this section

Pack-offs in this section can be caused by

- Swelling clay interaction between the formation and drilling fluid
- Accumulation of cutting due to washout

Based on the information from the end of well report, the following where reported (Saltnes & Gundersen, 2006):

- The caliper showed analysis in general the hole was enlarged in the shale formation and gauge in the calcite cemented sandstone
- The caliper log also showed that the shoulders are produced in the transition zone between over gauge shale and gauge calcite cemented sand stone
- Hole enlargement in soft shale in front of hard stringers increases with increased exposure time due to hydraulic and mechanical wear from bit and BHA

While tripping in hole three depth intervals created problem

- 5757+/-
- 5970+/-
- 6144+/-

All these depth are within shale with formation adjacent hard formation on both sides

One theory is that this enlarged intervals acts as cutting traps. When tripping in hole the bit comes from a gauge hole to an over gauge hole which also seems to have ledges, the bit/BHA could easily hand up there, and as result of that start of rotation and /or circulation to continue RIH lifts the cuttings trap. If at the same time some of the large OD components are within the gauge hole, erratic torque, slip-slip and pack offs could be the result.

The following are the snapshots to describe several pack-off tendencies in wellbore 34/10-48A 8 ½”

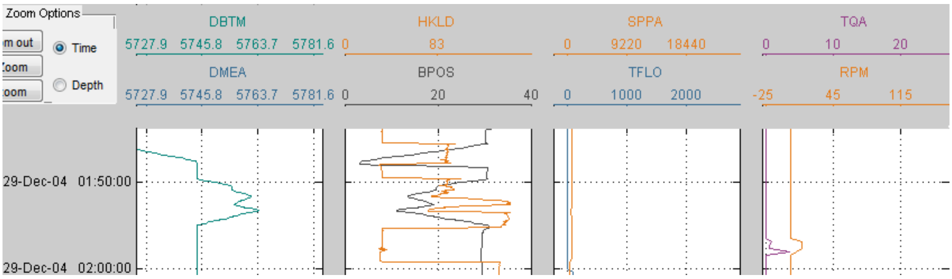

Figure 21: Case 1; took weight of 6 ton and 14 ton at 5757 m and 5764 m respectively during running in at 0.01 m/s in wellbore 34/10-48A, 8 ½” section (Data from Statoil via Verdande Technology).

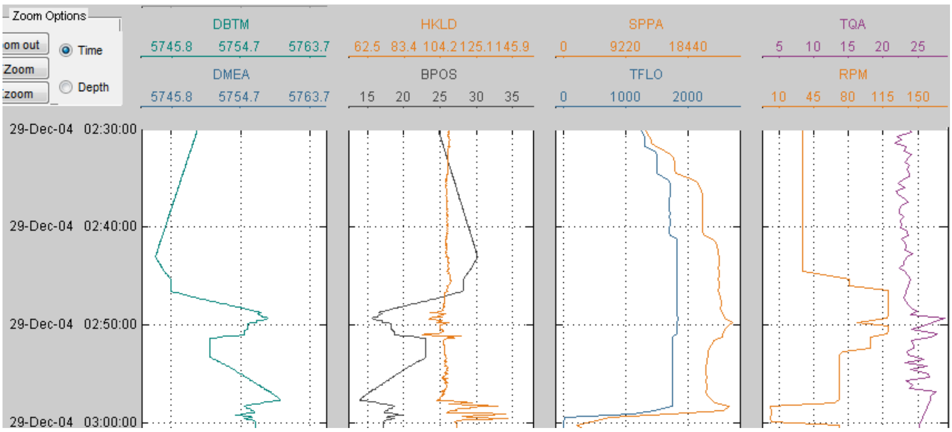

Figure 22: Case 2; Pack off tendencies at the 5752 m to 5755m during POOH at 0.01m/s at 02:50 in wellbore 34/10-48A, 8 ½” section (Data from Statoil via Verdande Technology).

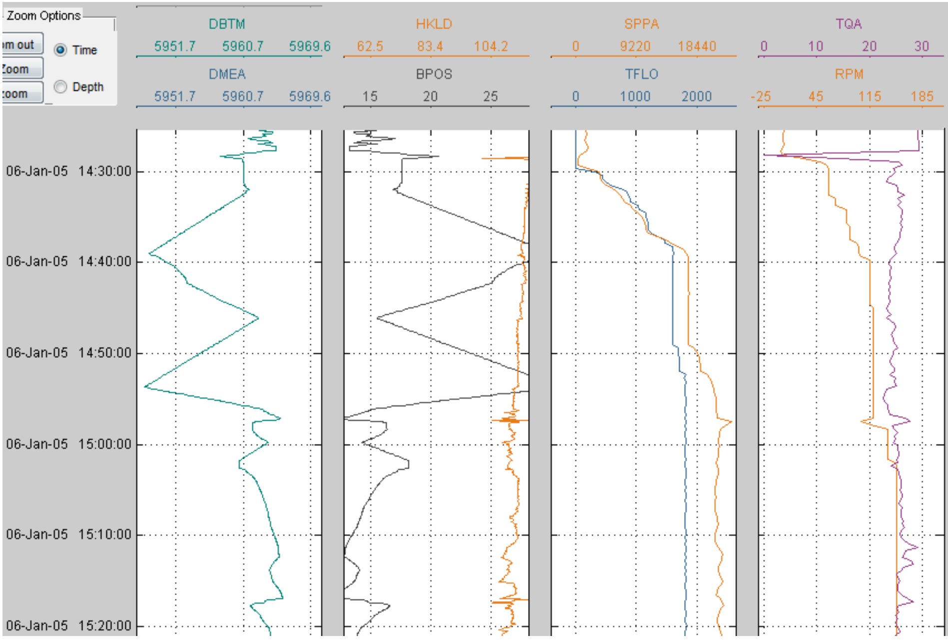

Figure 23: Case 3; worked tight interval from 5971 m to 5972 m after running in hole from 5970 m to 5971 m in wellbore 34/10-48A, 8 ½" section (Data from Statoil via Verdande Technology).

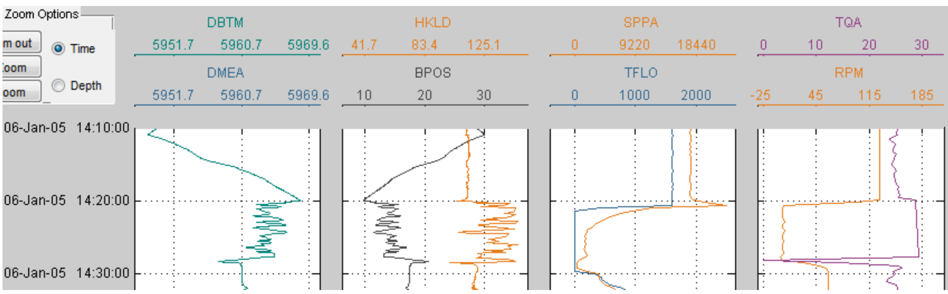

Figure 24: Case 4; Pack off at 5971 m during POOH at 0.01m/s in wellbore 34/10-48A, 8 ½" section (Data from Statoil via Verdande Technology).

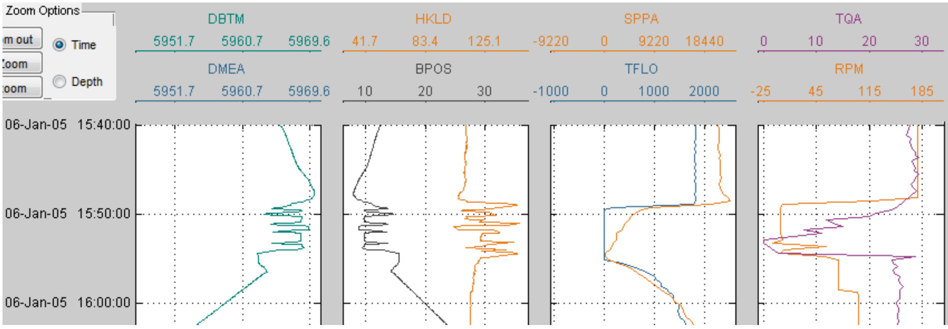

Figure 25: Case 5; Pack off at 5970 m supported by overpull and sudden increase in standpipe pressure at 15:50 during working of the string free in wellbore 34/10-48A, 8 ½" section(Data from Statoil via Verdande Technology).

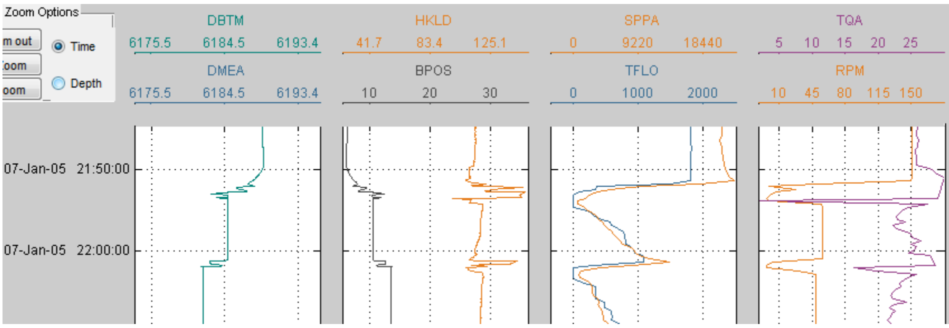

Figure 26: Case 6; Pack off at 6177 m and 6188 m during reaming down from 6140 m to 6189 m in wellbore 34/10-48A 8 1/2" section (Data from Statoil via Verdande Technology).

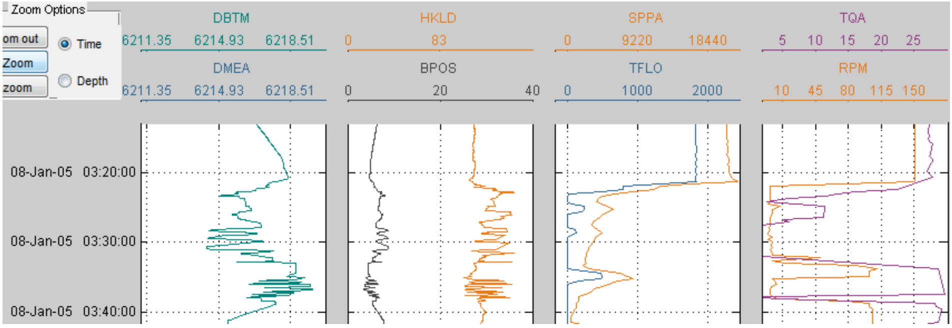

Figure 27: Case 7; Pack off at 6217 m during reaming down from 6189 m to 6217 m in wellbore 34/10-48A 8 1/2" section (Data from Statoil via Verdande Technology).

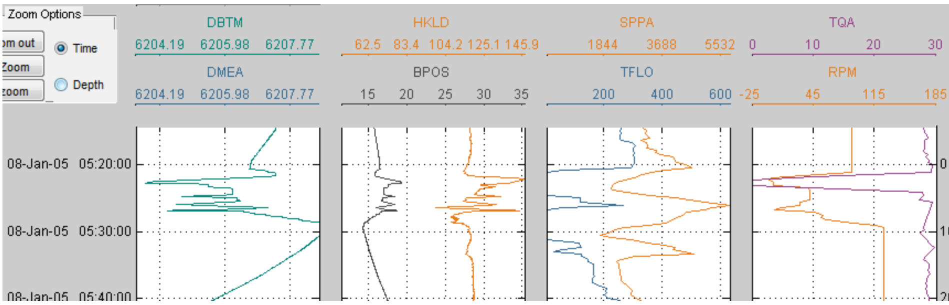

Figure 28: Case 8; Pack off at 6206 m during reaming back from 6214 m to 6199 m in wellbore 34/10-48A 8 1/2" section (Data from Statoil via Verdande Technology).

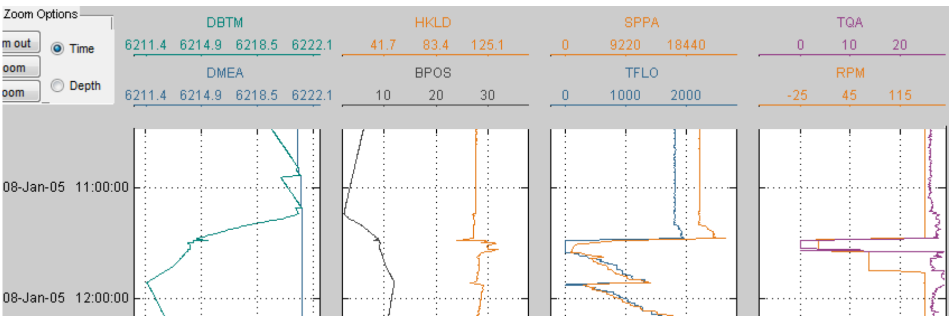

Figure 29: Case 9; Pack off tendencies at 6211 m and 6214 m during back reaming from 6221 m to 6208 m in wellbore 34/10-48A, 8 ½" section (Data from Statoil via Verdande Technology).

Static parameter for wellbore 34/10-48A

- Bit Type:MGR 741BPX[M222] by Smith Bit (EoW)
- Bit Size (previous section): 12 ¼" obtained from (EoW)
- Bit Size (present section): 8 ½" obtained from EoW

Static symptoms (ss)

- Fm Special expected (ss): No information in (EoW)
- Fm Boundary expected (ss): No information in (EoW)
- Fault Expected (ss): No information in (EoW)
- Fm Permeable expected (ss): No information in (EoW)
- Erosion wellbore factor (ss): No information in (EoW)
- MD Water Depth (ss): 216.9 m (EoW)
- MD Well (ss):6221 m RKB for wellbore 34/10-48A (EoW)
- Mud Type (ss): Versavert OBM
- Mud Weight (ss): 1.59 SG (EoW)
- Mud Weight Material (ss): Barite (EoW)
- Mud Water Activity (ss): 0.9 (EoW)
- Mud Yield Point (ss): 4.5-9.0 Pa (EoW)
- Shallow Gas Expected (ss):
- Well Inclination (ss): 86°
- Well Path (ss): deviated

The description why cases (1 to 9) are of wellbore wall type (Abnormal HKL type 1)

- High Mud Water Activity (ss) 0.9
- Presence of swelling materials (shale and Claystone), see table 12
- Long time. Well Openhole Very Long (ss) is defined as openhole> 1000m. in the wellbore 34/10-48A 8 ½" the section was drilled from 5100 m to 6221 m without casing hence the openhole time was very long
- Symptoms such as overpull, took weight, torque fluctuation and pack-offs were reported

Table 11: Two ways relationship for cases 1 to 9 for HKL type 2

Concept A causes > B	>	<	Concept B causes <A
Mud Water Activity High(ss)	4	0	Shale Swelling Invisible (i)
Shale Swelling Invisible (i) AND Time Long (s)	6	0	Shale Swelling (err)
Shale Swelling (err)	6	0	Wellbore Wall Restricted (i)
Shale Swelling (err)	6	0	Mud LGSC High(i)

Table 12: Formation description in wellbore 34/10-48A

Depth (m MD)	**Formation**	**Lithology**	**Swelling materials**
5105-5108 5611-5988 6136-6221	Heather Formation	Claystone Sandstone Limestone	*Claystone*
5158-5611	Tarbert Formation	Sandstone Shale Siltstone Stringers of limestone Seam of coal	*Shale*
5988-6067	Shetland Group	Claystone with stringers of limestone and marl	*Claystone*
6067- 6136	Cromer knoll Group	Limestone Claystone and marl stringers	*Claystone*

5.7.2 Cases from wellbore 34/10-C-47

In this section 7 hook load cases were presented through snapshots. The cases were obtained from the data given by Statoil via Verdande Technology. The cases were developed by consulting the end of End of Well report for wellbore 34/10-C-47 and opening RTDD through Matlab script for viewing well data created by Verdande Technology.

Description of revealed Cases

Case type: Abnormal HKL type 2

Data source: Statoil

Place of occurrence: Wellbore 34/10-C-47, 17 ½" section in Gulfaks field

The 17 ½" section was drilled in 3 runs. When pulling out of the hole after the first run the hole was circulated four times bottom up with 5000 lpm, 180 rpm when the pump pressure suddenly increased and hole partially packed off. At 1885 it was necessary to circulate well cleaned due to overpull and pack off tendencies. Circulation was established in steps to 5000 lpm and large amount of cuttings were coming over the shakers. 33 hours of circulation were necessary before the back reaming could commence. In total 96 hours were used to get out of hole. The BHA came out encapsulated in sticky cuttings (Christophersen et al., 2007).

When POOH at 2070 m (just in Balder) hole packed off after 4 x BU (drilled 556m with 65 % hole cleaning). Used 10 hours to establish full rate (3400 lpm, 180 rpm) again when pumping OOH again at 1875 hole packed off again. Used 12 hours to establish trend up to 5000 lpm, hence it was necessary to ream OOH.

Figure 30: Sticky cuttings coming over the shaker (Christophersen et al., 2007).

Figure 31: Cuttings found in bell nipple during clean up(Christophersen, Gjerde, & Valdem, 2007).

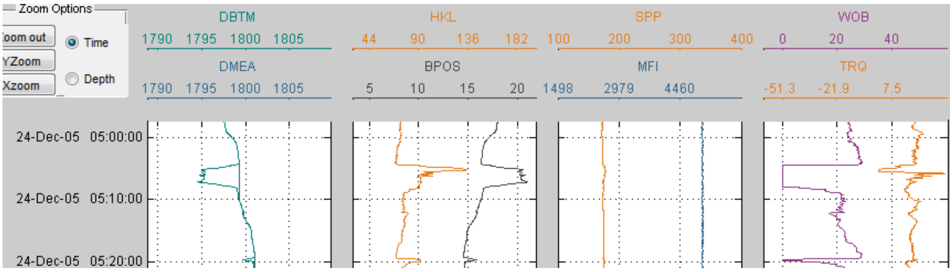

Figure 32: case 10: overpull at 1795 m due to key seat as no evidence of an increase in standpipe pressure to support pack off as the symptom. It occurred in wellbore 34/10-C-47 at 05:05:00; 24 .12.2005 in section 17 ½" (Data from Statoil via Verdande Technology).

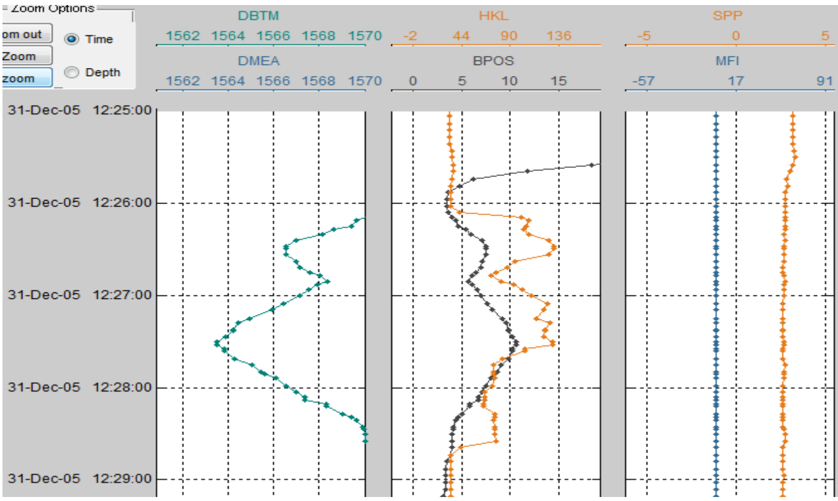

Figure 33: Case 11; Overpull at 1566 m and 1563 m during POOH at (12:26:00 to 12:28:00); 31.12.2005 in wellbore 34/10-C-47, 17 1/2" section (Data from Statoil via Verdande Technology).

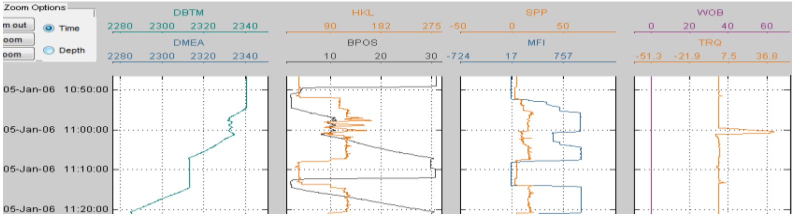

Figure 34: Case 12; Erratic HKL at 11:00:00; 05.01.2006 during circulating out to clean hole at 2335m in wellbore 34/10-C-47, 17 1/2" section (Data from Statoil via Verdande Technology).

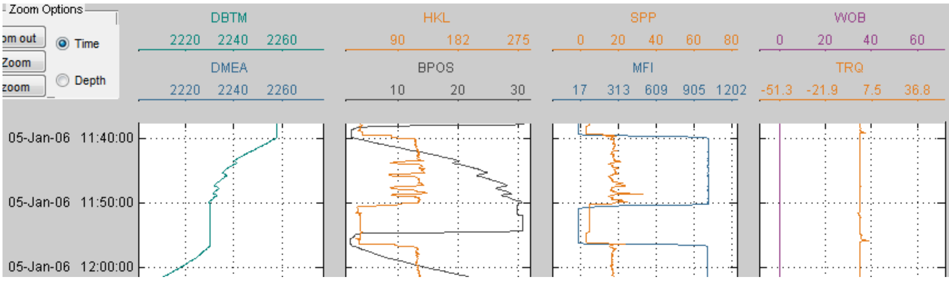

Figure 35: Case 13; erratic HKL at 11:45:00; 05.01.2006 during circulating out to clean hole at 2235 m in wellbore 34/10-C-47, 17 1/2" section (Data from Statoil via Verdande Technology).

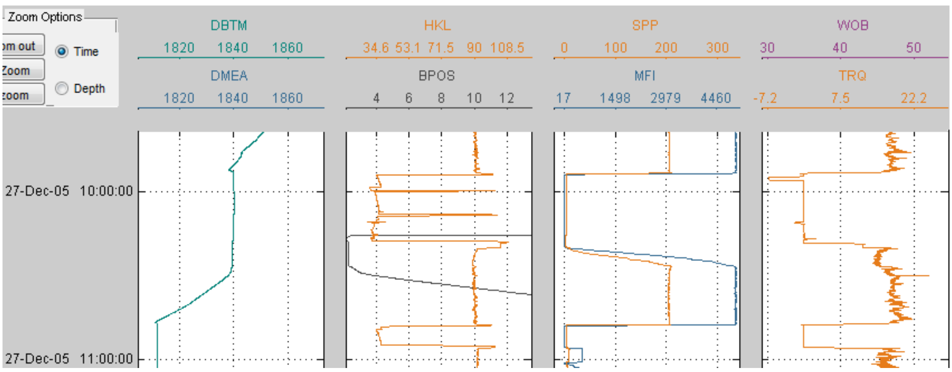

Figure 36: Case 14; overpull of 15 ton during pumping out of hole at 1840 m supported by increase in off-bottom torque in wellbore 34/10-47-C 17 ½" section (Data from Statoil via Verdande Technology).

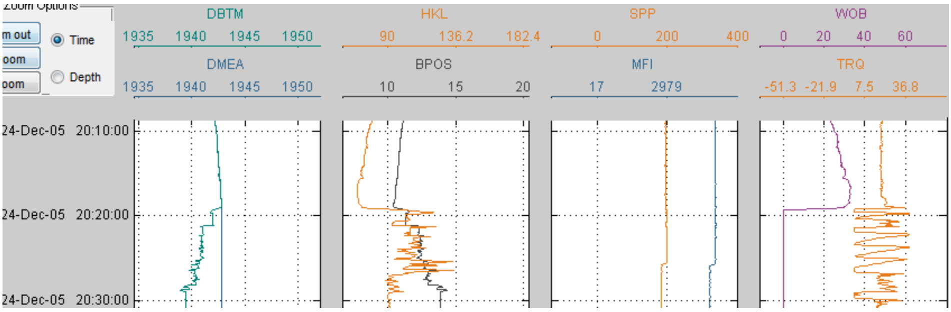

Figure 37: Case 15; erratic hook load and torque during POOH from 1944 m to 1938 m (20:20:00-20:30:00) in the wellbore 34/10-47-C 17 ½" section (Data from Statoil via Verdande Technology).

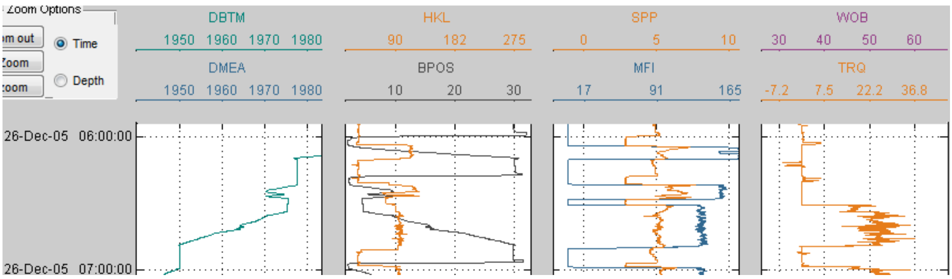

Figure 38: Case 16; Pack offs during circulating bottom up from 1980 m to 1950 m (06:30:00-06:50:00) in the wellbore 34/10-47-C 17 ½" section (Data from Statoil via Verdande Technology).

Static parameters for wellbore 34/10-C-47

- Bit Type: Milled Tooth Bit (EoW)
- Bit Size (previous section): 24" obtained from (EoW)
- Bit Size (present section): 17 ½" obtained from(EoW)

Static symptoms (ss)

- Fm. Special expected (ss): No information in (EoW)
- Fm. Boundary expected (ss): No information in (EoW)
- Fault Expected (ss): No information in (EoW)

- Fm. Permeable expected (ss): No information in (EoW)
- Erosion wellbore factor (ss):No information in (EoW)
- MD Water Depth (ss): 216.9 m (EoW)
- MD Well (ss):2379 m RKB in 17 ½" (EoW)
- Mud Type (ss): Ultradrill Water Based Mud (WBM)
- Mud Weight (ss): 1.59 SG (EoW)
- Mud Weight Material (ss): Barite (EoW)
- Mud Water Activity (ss): 0.9 (assumed)
- Mud Yield Point (ss): 9.0 Pa (EoW)
- Shallow Gas Expected(ss):
- Well Inclination(ss) : 72.56°
- Well Path(ss): deviated

The description why the cases (10 to16) are of cleaning of wellbore (Abnormal HKL type 2)

- Insufficient hole-cleaning with Ultradrill mud. The Ultradrill mud used in the 17 ½" hole was not considered suitable and resulted in high concentration of packed cuttings that could not be removed from hole with 180-200 rpm and 5000 lpm used while drilling (Christophersen et al., 2007)
- The well path is deviated with average well inclination above 70°. The deviated well leads to the formation of cutting bed due to rapidly reduction of settling distance, hence cuttings accumulation is likely to occur

5.7.3 Cases from AGR Database

In this section 10 downhole restriction cases were described. The cases were obtained from the AGR database. By consulting End of Well reports and taking into consideration operations before, during and after the incidence has occurred. The four out of 10 cases were discussed in more detail to give the overview of developing the cases. In addition, table **15** shows the summary of all 10 downhole restriction cases from AGR database.

Case 17: Differential sticking at 4122 m

(a) Well description

Well 2/1-4 was drilled utilizing the semi-submersible drilling rig Aladdin. The well covered the period of 2nd April to 4th August 1982 and reached a total depth of 4525 m. The objective of the well was to determine the size of the accumulation tested by 2/1-3 and also to evaluate the quality of upper Jurassic reservoir sandstone.

(b) General well information

Provided in the EoW report

Data source	AGR database by iQx software
Well name	2/1-4
Failure type	Differential sticking
Section	8 ½”
Depth of occurrence	4122 m
Non-productive time (NPT)	39 hours

(c) Summary of events before, during and after the failure

The pipe became stuck when running in hole for wiper trip to dress off cement plug in 8 ½" open hole. Reaming was performed from 4122 m to 4138 m. the pipe became stuck whilst making a connection with the bit at 4122 m. The pipe came free after having worked pipe and pumped pipelax for 39 hours. The estimated overbalance was 410 psi (28.3 bar), which minimized the differential pressure as the reason for the stuck pipe. There were some indications of tight hole when running in the hole even before 4122 m was reached. This cored section caused problem every time the string was pulled out of the hole and several hours were spent reaming the interval.

(d) What were causes of the failure

- High mud weight causing a pressure overbalances in the 8 ½" section. A mud weight of 1.64 sg was used to drill the shale interval from 3785 m to 3955 m. The density was gradually increased from 1.64 to 1.68 sg over several days.
- The presence of the permeable zone (sandstone) in the section, hence the extreme pressure exerted by the overbalance in the permeable sandstone should have an increase in the thickness of filter cake, hence causing the differential pressure situation
- The time taken during connection was enough for mud cake build up around the drill pipe

Case 18: Mechanical stuck pipe

(a) Well description

The main objectives for the well 7/4-1 were to test commercial reserves of hydrocarbons in Upper Jurassic of Alpha prospect and to establish the Jæren High Model analogy proven by the 7/7-2 discovery well.

(b) General well information

Provided in the EoW report

Data source	AGR database by iQx software
Well name	7/4-1
Failure type	Mechanical stuck pipe
Section	17 ½”
Well location	North sea Norway
Rig name	Deepsea Bargen
Depth of occurrence	1733-1757 m
Non-productive time (NPT)	1.5hours

(c) Summary of events before, during and after the failure

Drilled 17 ½” hole from 929 m to 1733 m. increased the mud weight from 1.5 SG to 1.60 SG, Continued drilling from 1733 m to 1757m. Had problem with pack off and were not able to rotate and circulate. Worked the string out to 1373 m were the string went stuck. After 1.5 hours the string was worked and jarred down to 1388 m. Finally circulation was established at 1530 m. Back reaming and pumping were necessary when pulling out of the hole. 1.9 SG high pill were also pumped and better cleaning was obtained.

(d) What are the causes of the failure

- Cuttings and sloughing formation pack off the annular space around the drillstring. From the EoW report it is reported that log showed a diameter was 20-21 inches from 1400 m to 1800 m while from 1880 m to TD the diameter was 18-19 inches. This indicates the presence of washout and hence cuttings can be accumulated that may lead to the pipe to stuck mechanically.
- Swelling formation can also be the cause of this situation. From the EoW it is stated that the 17 ½" section had several problems with tight hole and hence 1.90 SG heavy weight pills were necessary to lift out the large amount of cuttings. The large amount of cuttings and clayballs plugged the diverter housing and flowline several times.
- During the incident no circulation and rotation were possible. This is symptom of the string under mechanical sticking

Case 19: Bit Balling at 2141 m

(a) Well description

Well 2/2-5 was spudded on November 7, 1991. In the Nordland, Hordaland and Rogaland Groups, the well penetrated mainly Claystone with minor sandstones. The sandstones of the Vade Formation in the middle of the Hordaland Group proved to be water-bearing.

(b) General well information

Data source	AGR database by iQx software
Well name	2/2-5
Failure type	Bit balling
Section	17 ½”
Well location	North sea Norway
Rig name	Treasure Saga
Depth of occurrence	2141m

(c) Summary of events before, during and after the failure

A 17 ½” hole was drilled down to 2043 m while performing wiper trips every 200 m due to tight-hole sections, and at the same time increasing the mud weight to 1.45 sg. The drilling progressed to 2141 m where the bit was pulled due to severe bit balling. A new BHA was run in the hole, but went stuck at 2100 m. While working the drillstring, the circulation was gradually regained and the pipe was free at 2062 m

Table 13: Row of events before the bit balling at 2141m

Date	Time	Observation	Remarks
23/11/1991	23:00-24:00	Worked through Tight spot at 1850 m. washed and reamed from 1800 m to 2043 m	Tight formation due to swelling formation
24/11/1991	20:30-23:30	Drilled 17 1/2" hole from 2044 m to 2141 Had low ROP and Overpull during POOH	Low ROP and overpull are a symptoms of bit balling
25/11/1991	06:30	Losses over the shaker	Symptom of bit balling
25/11/1991	08:00	Low torque	Bit balled

(d) Why the failure is bit balling?

The failure occurred within the Hordaland Group (1608- 2746 m RKB MD) which is dominated by two thick Claystone sequences separated by an Oligocene sandstone unit named the Vade Formation. Claystone like shale consist of colloidal particles, has ability of coming in intimate contact with the rock bit or drill collar. Swellable, soft clay stick easily to steel surface since it is ductile and deformable, thus increasing the contact. Symptoms of the bit balling are(Skalle, 2014):

- Reduced ROP
- Increased SPP-due to reduced annular diameter
- Blocked shaker screen (soft clay seen)
- Overpull on tripping out

Of the above mentioned symptom three of which are reported in the end of well report, hence by including the factor of having Swellable material (Claystone). It is concluded that the failure type is wellbore dominated failure due to bit balling.

Case 20: differential sticking at 3183 m

(a) Well descriptions

Well 2/6-4 was dedicated to test the Jurassic prospect located in the Northern part of this block. The well was planned to stop at least 20 meters in the Triassic sequence. SSDV "West Vanguard" spudded in the well the 08.04.90 at 6H30, after 2 days of moving and anchor handling. The T.D. was reached the 24.05.90.

(b) General well information

Data source	AGR database by iQx software
Well name	2/6-4
Failure type	Differential sticking
Section	12 ¼”
Well location	North sea Norway
Depth of occurrence	3183 m
Non-productive time (NPT)	15 hours

(c) Summary of events before, during and after the failure

12 ¼" section was drilled from 2283 m to 3345 m with a KCL polymers mud (KCL content 70 to 25g/1). The string got stuck at 3183 m during connection with circulation but no rotation (m.w. 1.60). the well was circulated with 20 m^3 of Coatex pill (EMW 1.53). No result. Pumped 15 m^3 of mudban pill unweighted. Then, the Pipe was freed after 2 hours.

(d) Why the failure is differential sticking?

- Since the string got stuck during connection, it means the string was in contact with the wellbore for sufficient period of time. This contributed to the formation of mud cake around the string and hence led to stuck pipe
- Circulation was possible but no rotation. This is a symptom of differential sticking of the drillstring

Table 14 is an input to Table 15 for error type.

Table 14: Dominating error type

S/N	Dominating error type
1	Stability of wellbore wall
2	Cleaning of the wellbore

Table 15: Downhole restriction cases from AGR database

Case No	Well name	section	Failure type	Depth (m)	NPT (hours)	Error type	Main reasons for selecting type of error
17	2/1-4	8 ½”	Differential sticking	4221	39	1	• High mud weight (410psi overbalance) • permeable formation (sandstone zone) • stationary pipe while making connection
18	7/4-1	17 ½”	Mechanical stuck pipe	1733	1.5	2	• Not possible to rotate and circulate during stuck • Pack offs
19	2/2-5	17 ½”	Bit Balling	2141		2	• Low ROP • Low torque • Swelling material (Claystone)
20	2/6-4	12 ¼”	Differential sticking	3183	15	1	• Circulation was possible but no rotation • Stuck during connection, enough time to filter cake build up
21	7/7-1	17 ½”	Tight hole	1513		1	• Gumbo Problem
22	7/11-9	12 ¼”	Stuck pipe	3710	126	1	• Tight hole
23	30/2-1	12 ¼”	Stuck pipe	3486	7	1	• Tight hole
24	30/6-10	12 ¼”	Stuck pipe	2665	32.5	1	• Swelling formation (shale)
25	33/9-18	12 ¼”	Differential sticking	3512	83.5	1	• Permeable formation (sandstone)
26	34/7-1	17 ½”	Stuck pipe	1274	72	1	• Swelling formation (Claystone)

6. Self- assessment

(a) Application of this work

By knowing the HKL signature it is possible to combine it with the relations between concepts in knowledge model or ontology engineering. This enables identification of the type of restriction (cleaning of the wellbore, stability of the wellbore wall or others). Once the type of restriction is known it is possible to take the correct remedial actions to rectify the condition. Rectifying the condition reduces cost and NPT, hence improve the drilling operations.

(b) Shortcomings of this work

- The two wells, 34/10-C-47 and 34/10-48A used in studying hook load response were in the same field (Gullfaks C field); hence there was a similarity in the geological formation. Since the geology determines the type of downhole restriction, it was important to have wells from different fields for more analysis of the HKL response
- No data agent was created to detect evidences of Poor hole-cleaning or of Wellbore Instability using Hook load response
- Only 2 out of the 12 wells used in finding evidences of Poor hole-cleaning or of wellbore instability through HKL response had RTDD. Therefore, this work contains cases with hook load response from the two wells which is not sufficient
- For cases 1 to 9 for well 34/10-48A, the causes for downhole restriction were considered to be swelling clay only.

- Lack of enough explanation on distinguishing between the HKL deviation, that is, HKL deviation due to wellbore wall or HKL deviation due to wellbore

(c) Future improvements

- More wells from other fields apart from (Gullfaks C) should be considered in studying hook load response for more analysis. This will improve the study as it will give wide range of comparison
- The data agents need to be created to show these HKL responses, hence improve the drilling operation by reducing downtime due to downhole restrictions
- More wells containing RTDD should be given. This will enable access of more cases from varieties of incidences reported. It will also answer the thesis tittle suitably as it states "Evidences of Poor hole-cleaning and Wellbore Instability using hook load response"
- A row of events for each developed case should be included. This will be helpful in creating ontologies for the HKL cases. This should go parallel with a detailed evaluation and testing of cases
- More information on what distinguish the two types of restriction (stability of wellbore wall and cleaning of wellbore) should be given

7. Conclusion

From the work performed (finding evidences of poor hole-cleaning or of wellbore instability using HKL response), 26 downhole restriction cases were obtained from the studied 12 wells. From these cases, the following conclusions were drawn:

- Cases 1 to 9 were 45% and 55% caused by cuttings accumulation and swelling clay respectively. The main cause of deviation in hook load was the swelling wellbore. The cases were classified as Stability of wellbore wall
- Cases 10 to 16 were 35% and 65% caused by swelling clay and cuttings accumulation respectively. The main cause of deviation in hook load was cuttings accumulation. The cases were classified as cleaning of the wellbore
- Cases 17, 20 to 26 were in most cases caused by swelling of the wellbore while cases 18 and 19 were due to accumulation of cuttings in the wellbore
- The snapshots for HKL response are useful in creating the data agents to detect the downhole restriction before it occurs or become serious.
- Distinguishing the two scenarios (HKL deviation due to wellbore restriction and HKL deviation due to wellbore wall) was a challenging task. With the help of ontology engineering it was possible to distinguish the two. Therefore, ontology engineering should be included when distinguishing the case type as it gives main cause by finding probability of it.

8. Nomenclature

8.1. Abbreviation

BHA	Bottom Hole Assemble
BPOS	Block Position
BU	Bottom Up
CBR	Case Based Reasoning
DBTM	Bit depth
DMEA	Measured depth
ECD	Equivalent Circulating Density
EoW	End of Well Report
HKL	Hook load
HKLD	Hook load
MBR	Model Based Reasoning
MWD	Measurement While Drilling
N/A	Not applicable
NPT	Nonproductive Time
OBM	Oil Based Mud
OD	Outside Diameter
OOH	Out of Hole
POOH	Pulling Out of Hole
ROP	Rate of Penetration
RPM	Revolution per minute
RTDD	Real Time Drilling Data
SPP	Stand Pipe Pressure
SPPA	Stand pipe Pressure average
TD	True depth
TQA	Torque
TQR	Torque
TVD	True vertical depth
WOB	Weight on bit
WODS	Weight of drillstring

8.2. Symbols

B	Weight of travelling block
F_f	Force of coulomb friction
F_n	Normal force
μ	Coefficient of friction (COF)
f_b	Borehole mechanical friction factor
f_{bn}	Borehole normal mechanical friction factor

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10. Appendix

IMPORT SCRIPTS FOR VIEWING WELL DATA

Two Matlab scripts developed by Verdande Technology were used for viewing historical RTDD for the two different wells namely; 34/10-C47 in 17 ½" section and 34/10-48A in 8 ½" section. Snapshots for identifying evidences of poor-hole cleaning or of wellbore instability were then obtained using Hook load response from running these scripts

Import scripts for wellbore 34/10-47-C 17 ½"

```
%%%%% IMPORT SCRIPT FOR VIEWING WELL DATA
%
% By: Espen Birger Raknes, espen.raknes@ntnu.no
% V: 2014-10-09
%
clear all
clc

%% SETUP
% Here you can change the contents:
filename = '17_5_fixed.mat';     % Filename to be loaded. Must be .h5 format or .mat
section = '47';                  % Put to 47 for 47C and 48 for 48A

op_system = 'windows';           % Operating system that you're running on
screenx = 1024;                  % Screen width for plot window
screeny = 768;                   % Screen height for plot window

%% DO NOT EDIT BELOW HERE (if you don't know what to do...)!
% Importing libraries
addpath('lib');

% Importing file. Checking if it is a H5-file or a .mat file
current_dir = pwd();
[pathstr,name,ext] = fileparts(filename);

if(strcmp(ext,'.h5'))
   X = importH5(fullfile(current_dir,filename));
else
   load(filename);
end
% Plotting
```

```
tagged = [];
recognized = [];
if(section == '47')
    viewgui(screenx,screeny,op_system,[],[],'Time',...
        X,...
        'DMEA','DBTM',[],...
        'BPOS','HKL',[],...
        'MFI','SPP',[],...
        'TRQ','WOB',[],...
        [1 0 0 0],recognized,tagged);
else
    viewgui(screenx,screeny,op_system,[],[],'Time',...
        X,...
        'DMEA','DBTM','SWOB',...
        'BPOS','HKLD',[],...
        'TFLO','SPPA',[],...
        'RPM','TQA',[],...
        [1 0 0 0],recognized,tagged);
end
```

Import scripts for wellbore 34/10-48A 8 ½”

```
 %%%% IMPORT SCRIPT FOR VIEWING WELL DATA
%
% By: Espen Birger Raknes, espen.raknes@ntnu.no
% V: 2014-10-09
%
%% SETUP
% Here you can change the contents:
filename = '48A-mod.mat';  % Filename to be loaded. Must be .h5 format or .mat
section = '48';            % Put to 47 for 47C and 48 for 48A

op_system = 'windows';     % Operating system that you're running on
screenx = 1024;            % Screen width for plot window
screeny = 768;             % Screen height for plot window


%% DO NOT EDIT BELOW HERE (if you don't know what to do...)!
% Importing libraries
addpath('lib');

% Importing file. Checking if it is a H5-file or a .mat file
current_dir = pwd();
[pathstr,name,ext] = fileparts(filename);

if(strcmp(ext,'.h5'))
    X = importH5(fullfile(current_dir,filename));
```

```
else
   load(filename);
end

% Plotting
tagged = [];
recognized = [];
if(section == '47')
   viewgui(screenx,screeny,op_system,[],[],'Time',...
      X,...
      'DMEA','DBTM','WOB',...
      'BPOS','HKL',[],...
      'MFI','SPP',[],...
      'RPMB','TRQ',[],...
      [1 0 0 0],recognized,tagged);
else
   viewgui(screenx,screeny,op_system,[],[],'Time',...
      X,...
      'DMEA','DBTM','SWOB',...
      'BPOS','HKLD',[],...
      'TFLO','SPPA',[],...
      'RPM','TQA',[],...
      [1 0 0 0],recognized,tagged);
end
```