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Reveal the Cause of Downhole Restrictions by Means of Knowledge Engineering

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Abstract

Stuck pipe is an example of an unwanted problem that causes high NPT and seems to occur again and again. As 50 % of all stuck pipe incidents occur during tripping, increased knowledge about how to recognize progressing downhole problems are needed. Early warnings of stuck pipe are HKL restrictions, and early warnings of HKL restrictions are symptoms. If the symptoms seen at surface can be related to a HKL restriction type, preventing actions can be initiated at an early stage, and stuck pipe can be avoided.

Four main causes of HKL restrictions have been analysed and related to symptoms that can be recognized at the surface. The main causes are accumulating cuttings, mechanically unstable wellbore, chemically unstable wellbore and local dogleg. By means of the Knowledge Model, relationships between the symptoms and the main causes were determined. The strength of the relation between each symptom and the restriction cause was found and proved diversity among the main symptoms of each restriction cause.

21 cases of HKL restrictions were found from drilling reports and RTDD obtained from Statoil. Symptoms interpreted from the drilling reports were used as input for the Knowledge Model which revealed the main cause of the restriction. The model proved that 14 of the 21 restriction cases were caused by the error Reactive Formation.

The HKL signature of the 21 cases was interpreted and related to the restriction causes. The interpretation showed that the signature of cuttings accumulating can be separated from the signatures of mechanically instability.

Five restriction events were analysed using the Knowledge Model. The main cause of the restriction events were found proving the Knowledge Models ability to determine the restriction cause of downhole problems. The analysis proved that Reactive Formation was the most frequent error to cause HKL restrictions, with explanatory strength of 48 % as the highest in average.

Samandrag

Så mange som 50 % av alle hendingar der borestrengen settes fast i brønnen skjer ved trippingoperasjonar. Auka kunnskap om kva som er årsaka til at borestrengen settes fast ved trippingoperasjonar, kan føre til minka ikkje-produksjonstid og færre stuck pipe hendingar. For at det skal bli mogleg må dei tidlege symptoma på stuck pipe bli betre kjende. Tidlege tegn på stuck pipe er kroklastrestriksjonar, og symptom er igjen tidlege tegn på korklast restriksjonar. Dersom symptoma som blir sett på overflata kan bli relatert til sin korrekte kroklastrestriksjon, kan forebyggjande tiltak bli iverksat i ein tidlegare fase og stuck pipe bli forhindra.

Fire hovudgrupper av kroklastrestriksjoner har blitt analysert og relatert til symptomar som kan bli sett på overflata. Dei fire hovudgruppene er: akkumulasjon av hullkaks, mekanisk ustabil brønn, kjemisk ustabil brønn og lokal dogleg. Ved hjelp av kunnskapsmodellen har relasjonar mellom symptoma og restriksjonane blitt funne. Denne styrken er funne for kvart symptom, og viste at hovudsymptoma som peikar på kvar restriksjon er ulike.

Frå borerapportar og notids boredata blei det oppdaga 21 tilfelle som førte til auka kroklast. Ut frå rapportane blei symptom som kan ha vært årsaken til restriksjonstilfella plukka ut og tolka. Symptoma blei innmata i kunnskapsmodellen som på den måten bestemte hovudårsaken til restriksjonstilfella. Analysed viste at 14 av den 21 tilfella var forårsaka av feilen Reaktiv Formasjon.

Kroklast-signaturane til dei ulike tilfella blei tolka og relatert til kvar sin hovudårsak. Tolkinga viste at signaturen som kan bli observert når borekaks akkumulerer i brønnen, kan skiljast frå signaturen når det er resrtiksjonen er forårsaka av mekanisk hullstabilitet.

Fem restriksjonshendingar blei plukka ut frå dei sju brønndatane som var tilgjengelige. Ved hjelp av kunnskapsmodellen blei hovudårsaka til restriksjonane bestemt og viste med det at modellen kan bli brukt til å bestema årsaka til nedihullsproblem. Analysa viste og her at Reaktiv Formasjon var den feil-gruppa som mest hyppig forårsaka kroklast restriksjonar. Den forklarande styrken til Reaktiv Formasjon blei 48 %.

Preface

This thesis was written in the spring semester 2013 and presents my work in TPG4910 Drilling Technology Diploma Thesis at The Norwegian University of Science and Technology (NTNU).

First of all I would like to say that I am very grateful for all help, guidance and continuous feedback during the semester given by my supervisor Pål Skalle (Associate Professor, Drilling Engineering, NTNU) throughout the semester. I would also like to thank my fellow student Hanne Bjerke (Fifth year student, Drilling Engineering, NTNU) for interesting discussions regarding HKL restrictions and signatures.

Last but not least, I would like to thank all the girls in room number 108 for numerous laughs and coffee breaks, in addition to long hours spent gathering motivation in the climbing wall at Dragvoll. Thanks for all the good memories we have together, I will keep them with me.

I hereby certify that this work is exclusively my own.

Trondheim, June 2013

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1. Introduction

Motivation

Oil wells today are becoming longer, deeper and more complex. The cost of drilling operations increase, causing increased economic consequences in case of non-productive time (NPT). NPT is caused by any failures that occur during the drilling operation, either due to downhole restrictions or unplanned surface activities delaying the operation. With daily rates of drilling an offshore well at approximately 300 000 US $ / day (Rigzone 2013), cost-efficiency has never been more important. If developing downhole restrictions can be recognized and diagnosed at an early stage, the problems can be solved effectively and NPT can be reduced.

In order to handle the developing hook load (HKL) restrictions correctly, increased knowledge about how to recognise and differentiate between the restrictions, is needed. Early warnings of HKL restrictions, are symptoms that can be seen at the surface. If the symptoms can be related to the HKL restriction type, preventing actions can be initiated before severe problems occur.

Today, restrictions are usually solved by initiating "Best Practice" straight after the first symptoms are seen. The drilling crew are then relying on the magnitude of the symptom, instead of the cause of it, when the preventive actions are initiated (Skalle et al. 2013). If the HKL restriction cannot be solved by "Best Practice", failures such as stuck pipe and collapsing hole, may occur. Cuttings accumulating, unstable wellbore, ledges, swelling wellbore etc., are all unwanted, complex events that tend to happen again and again, and may result in failures the correct preventive actions are not initiated. The driller have to be able to recognize the symptoms of a give restriction type in order to react accordingly and prevent downhole problems.

At the time of the downhole restriction, the HKL signal seen at surface will change. The HKL signal originates from real-time drilling data (RTDD) obtained from the monitoring systems gathered during tripping operations. The measured data will most of the time display a straight, constant line, indicating a smooth and clear hole. Sometimes curves deviating from normal will appear, depending on the conditions in the open hole (Cordoso et al. 1995). The deviations are referred to as HKL signatures and will appear if any restrictions are met during tripping. If the symptoms can be put in context with the HKL signal appearing at surface at the time of the restriction, the downhole restriction may be determined with high accuracy.

Drilling oil wells is complex operations which requires huge amounts of data and knowledge. A method of assisting these complex operations is Knowledge Engineering (KE). Knowledge Engineering is the method of collecting, reusing and sharing knowledge obtained from articles, cases and other sources, and is now frequently used for that purpose in the industry (Strube 1992). Knowledge Engineering has in the recent years been developed to enhance terms like the Knowledge Model (KM). The Knowledge Model is a tool that can be used to find relationships between the symptoms seen at the surface and the resulting error or failure. By means of the Knowledge Model, the restriction cause can thus be determined based on symptoms seen during the drilling operation, and other additional information about the restriction event. Any new relationships can be stored in the model to be used for similar restriction causes in the future.

Goal

The long term goal of this thesis is to give advises on how to most effectively repair a problem during drilling by revealing the cause of hook load restrictions, which is the short term goal of present thesis' work:

- Find a large number of restriction cases from historical logs, arrange them in logical cause groups and determine the cause of the restriction
- Determine the cause of the restriction cases based on the symptoms by means of the Knowledge Model
- Develop the Knowledge Model to enable reveal actions of the cause of the restrictions

Approach

Cases of HKL restrictions and their symptoms will be found from the RTDD delivered by Statoil. By means of the Knowledge Model, the different cases of borehole problems occurring during tripping will be evaluated and analysed to determine the cause of the restrictions. The HKL restrictions will be evaluated and related to the cause groups. The cause groups are predetermined and the result of the evaluation is that each group is defined by specific symptoms recognized from the RTDD. Five main restriction events from a full tripping operation will be analysed.

2. Related Research within Knowledge Engineering

Stuck pipe results in huge costs and unwanted NPT. A number of tools and methods are available to prevent stuck pipe and near stuck pipe incidents, each tool and method with its own advantage and limitation. One of the goals of this thesis is to use real-time drilling data (RTDD) to find and relate symptoms observed during the drilling process, to their belonging restriction causes by means of the Knowledge Model. In that way, the cause of HKL restriction can be revealed on surface during the drilling operation and actions to prevent stuck pipe can be initiated.

This chapter will give an overview of different methods and projects for preventing stuck pipe within Knowledge Engineering, before the method of knowledge modelling, will be presented. Chapter 3 will present how the Knowledge Model are adapted and used to analyse four main causes of HKL restriction cases. Chapter 4 will present how the available data was utilized to determine and find symptoms. Chapter 5 presents the results from the field analysis while Chapter 6 evaluates the results.

2.1 Previous Related Research

Computerized tools are developed to provide both automatic control of the operation as well as to function as decision support for the crew and operators. The tools are based on numerical models, experience from similar situations and reasoning by knowledge models. Substantial research has been done on the first two tools, and lately, increasing amount of research has been done on systems that utilize knowledge-based decisions. The increasing research trend is mainly due to todays need for human experience as the drilled wells are becoming deeper and more complex. Another reason is the potential crisis that may develop when people with long experience in the industry retire, leaving a gap of graduates with need for stored knowledge (Skalle et al. 2013).

The scope of this thesis is to improve the drilling operation in real-time by combining mathematical models with knowledge-based tools; i.e. the Knowledge Model. Previous research on this area has been done, but it has not included mathematical models. An example is the CODIO-project, where a statistical approach was taken. A Bayesian network that uses the difference between dependencies and independencies as variables was created. The network combines numerical and categorical parameters to generate the result. Another project developed for the analysis of the Daqing Oil Field, created a knowledge-based tool that supervises the drilling-bit conditions real-time as well as to do a bottom-up research approach when the failure situation (Skalle et al. 2013).

Abdollahi (2008) developed a causal model to detect well leakages. Different cases of leakage were sorted into five cause groups describing the main cause of the leakage. Shokouhi (2009) presented a project where the theory of Model-Based Reasoning (MBR) and Case-Based Reasoning was utilized and combined to create an extended version of CREEK. CBR will then contribute with the general knowledge while MBR is valid when the relations are expressed with a degree, i.e. causes always, causes sometimes. The result showed that by combining different methodologies, the reasoning result was improved (Skalle et al. 2013). The two projects did not however, include real-time data to identify the failures addressed, as will be done in this thesis.

Skalle et. al (2013) have recently started to develop a model to recognize the cause of drilling problems from RTDD based on the methodology of MBR. The model will be the basis of the theory behind this thesis, as well as when the cause of the restriction is determined.

2.2 Solving Drilling Problems through Knowledge Engineering

Knowledge engineering, or ontology engineering, has in the recent years been a method of reusing and sharing knowledge, and is now frequently used for this purpose on the industry. The term ontology is usually used for philosophy where it describes the study of "what is". Recent development of ontology within the area of engineering has applied the theory of ontology to create and enhance terms including the Knowledge Model, Data Model etc. (Skalle et al. 2013).

A simplified description of ontology is the creation of a hierarchy viewed as a schematic network, consisting of entities and relations. An overview of the main elements which creates the ontology hierarchy and is adapted to fit this thesis, is illustrated in figure 2.1. The figure illustrates a strong coupling between the cases and the general domain knowledge. This is the scenario for the CREEK system (Aamodt 2004). The CREEK system will for this thesis be used for the graphical display of the results where each node represents a symbolic concept in the KM and each link represents the relationship between the concepts. The CREEK system will in addition be used to support the analysis when knowledge stored in the CREEK system are used to find additional relationships and symbolic concepts during the field analysis.

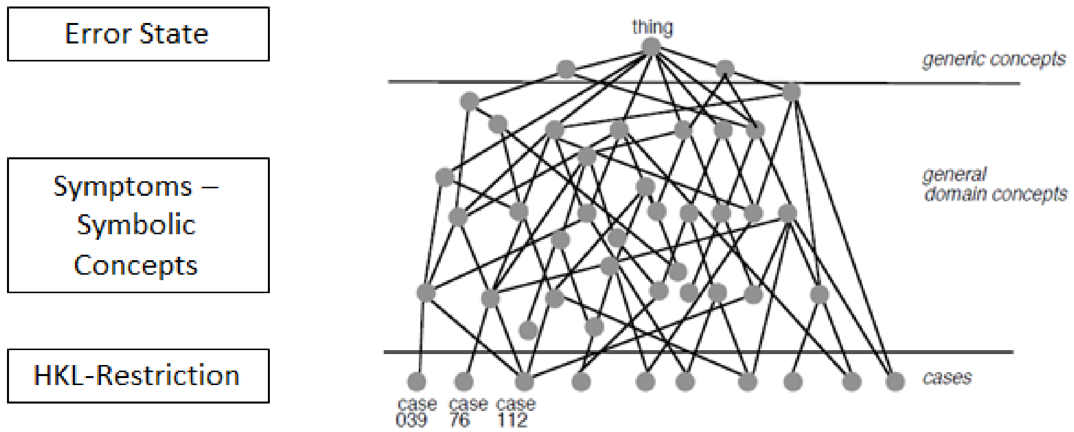

FIGURE 2.1: Coupling between cases and the general domain knowledge (Aamodt 2004)

As for most ontologies, the top-most concept is Thing, which can be anything in the world that has a meaning or is worth mentioning. The generic concepts include the process or the state, the state to be evaluated in this thesis is the error state. The network continues with the general domain concepts, which is where the symptoms are related to the symbolic concepts. Symptoms occur when the process move into error state and are related to symbolic concepts to give them a simple description and make them re-usable. Examples of symptoms and its symbolic concept is: "Increased ROP" – "Soft Fm. Drilled". The network ends at the cases which is the description of the problem (Skalle et al. 2013).

An ontology is usually developed either through a top-down process, bottom-up process or a combined process (Abdollahi 2007). A bottom-up process is the opposite of the top-down process and is the process of developing the model continuously during the data analysis. The bottom-up process is the process that will be used for this thesis.

In this thesis, the theory of CBR will create the basis for the investigation of HKL restrictions. CBR is a recent approach to solving problems through stored knowledge. Complex happenings from the field analysis are compared to similar happenings in already solved cases and transformed into simple events. The new events are easy to understand and can be used as input for the model to solve the problem of the current case. The most important characteristics of the restriction are still included, in addition to the unique features of the restriction. In order to identify similar patterns and features characterizing each restriction cause, similarities between them are important to discover. The similarities may create the basis for future learning and development within the drilling industry, and thus prevent the next stuck pipe or near stuck pipe incident in the future.

To easier describe the process of CBR, the CBR cycle is illustrated in figure 2.2. A case similar to the incident is first retrieved to see if it can be reused for the current case. If not, the retrieved case is revised and adapted to fit the current case before it is retained for future use. In that way the knowledge is increased and the model is expanded. The four steps of the CBR cycle is (Aamodt and Plaza 1994):

1. Retrieve: Find the most recent similar solved case
2. Reuse: Copy or integrate a proposed solution for the retrieved case

3. Revise: Adapt the retrieved case to fit the current case

4. Retain: Store the new modified case for future use

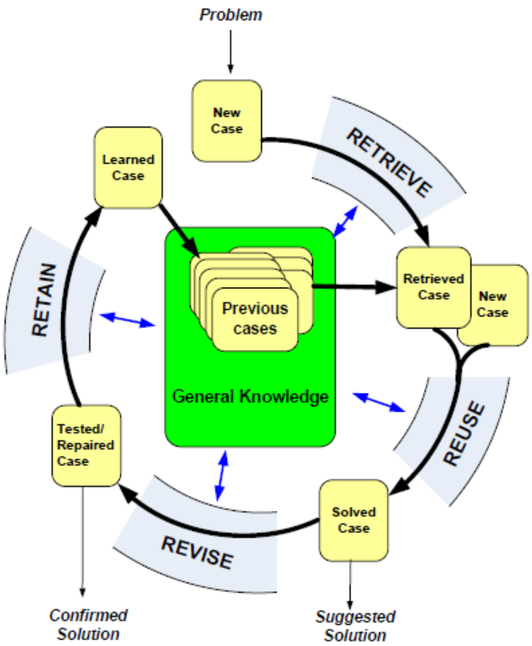

FIGURE 2.2: Three elements that builds the ontology hierarchy structure (Aamodt and Plaza 1994)

Put in context with the process of this thesis:

- Step one: Compare symptoms from the drilling reports to the symptoms in table B.1 – B.4 in Appendix B
- Step two: Reuse the symptoms and their relationships that are already stored in the table
- Step three: Adapt the symptoms if needed
- Step four: Any new symptoms and relationships found during the field analysis are added to the table

As mentioned, the CBR methodology will be used to discover similarities between the new events and already solved events. For the further analysis, the theory behind MBR will be utilized to create the relationships between the symptoms, symbolic concepts and failures. Information are gathered from historical RTDD of hook load restriction cases and adapted to be used as input for the Knowledge Model. The Knowledge Model will be used to create cause-effect chains and find main cause of each restriction as a numerical value (Abdollahi 2007). The KM will be presented in the following section.

Knowledge Model

As mentioned above, the KM is developed based on the theory of ontology engineering. The method of knowledge modelling makes it possible to reveal the main cause of restrictions or other problems occurring during drilling. Knowledge modelling is a combination of top-down and bottom-up approach; top-down is the initial knowledge process and bottom-up is when the model learns when new cases are solved (Aamodt 2004).

The inputs for the model will be observations, or symptoms, recognized before, during or after the drilling process. The symptoms are anything that deviated from the normal behavior or that contributed to the discrepancy. Example of a symptom leading to the failure Hole Cleaning Operation is "Low RPM". Low RPM in the period before the pipe got stuck may have been the cause or the contributing cause of the hole cleaning failure. If a number of different symptoms from the drilling operation are gathered, the symptoms can be related to the failures and the most likely cause of the downhole problem can be determined.

The symptoms have to be re-named and simplified before they can be used as input for the model. The symptoms will be tranformed into symbolic concepts, which are a short and specific description of the observation, making the problem easy to understand and giving the symbolic concept the ability to be stored and used for a similar case in the future (Skalle 2012). The symbolic concepts are related to groups and subclasses of different errors and failures.

The symbolic concepts have to be inserted at their correct place in the model. The placement in the model depends on the failure state or the error state, the technical failures and errors included in the KM are shown in figure 2.3 and figure 2.4, obtained from the CREEK system. When new concepts are found during an investigation, the KM is expanded and its competency to contribute to similar incidents in the future increases.

As mentioned, the symbolic concepts will be related through different relationships. The relationship is created depending on the strength between the concept

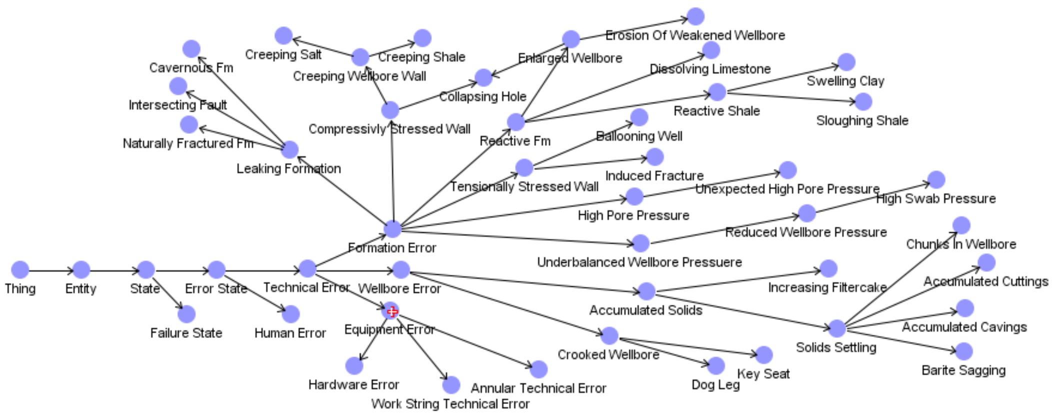

Figure 2.3: Technical Errors in the Knowledge Model

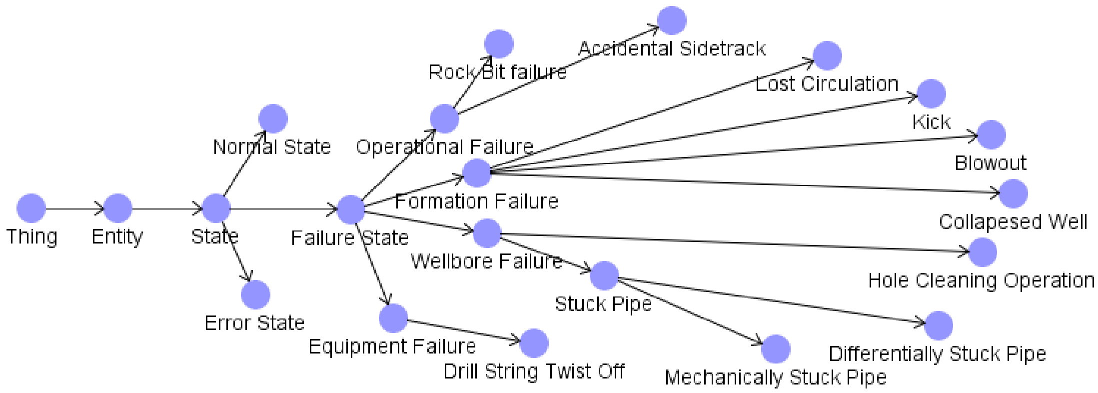

Figure 2.4: Technical Failures in the Knowledge Model

and its subclass. The strength of the relationships represents the certainty/uncertainty of the relation between two symbolic concepts. Table 2.1 gives and overview of the relationships and their numerical value (Skalle 2012).

Table 2.1: Relationships and their numerical value

Relationship	Numerical value
Causes always	1.0
Causes	0.9
Leads to	0.8
Implies	0.7
Causes sometimes	0.6
Enables	0.5
Reduces effort of	0.5
Involves	0.5
Indicates	0.4
Causes occasionally	0.3

It is possible for all relations to be inverse, i.e. "A leads to B" can also be expressed as "B is led to by A" (Abdollahi 2007).

The result of the KM is a numerical value. Each path consisting of symbolic concepts related to each other by different relationships has a specific value. The value presents the path strength, calculated from (2.1), is the product of the strength of each relationship from the first symbolic concept to the failure. The relationship between the observation and the symbolic concept is always equal to 1. (Skalle 2012):

$$path\ strength = \prod_{i=1}^{n} relation\ strength_i \tag{2.1}$$

Where n is the number of relations in the path

The final step when creating the KM is to relate the symbolic concepts to their error. This is done by calculating the explanatory strength. The explanatory strength is found by adding all the paths that lead to the same error (Skalle 2012), this can be done from Equation 2.2. For this case, the error represents the five restrictions presented in Chapter 2. By calculating the explanatory strength for each error, the result will show how each restriction is related to the causes.

$$explanatory\ strength = \sum_{k=1}^{m} path\ strength_j \tag{2.2}$$

Where m is the number of paths leading to the failure

To illustrate how the path strength is calculated, an example can be seen in Table 2.2. The path strength is calculated by 2.1.

Symptom	**Relation**	**Symbolic Concept**	**Relation**	**Error Subclass**	**Path Strength**
Shallow Depth	causes	High Montmorillonite Content	implies	Reactive Shale	$0{,}9 \cdot 0{,}7 = 0{,}63$

TABLE 2.2: Example of a calculation of one path strength

The Knowledge Editor CREEK will be used to display the results from the field analysis. In this thesis, the CREEK system will be used to demonstrate the relationships between symptoms, symbolic concepts and errors. The Creek system is a software tool that includes the methodology of CBR. Field cases are used as input for the system, and are thus included in the general domain knowledge. The input values can then be related to the stored domain knowledge by different causal relationship strengths and the root cause of the problem may then be determined (Abdollahi 2007).

3. KM Applied to Solve Drilling Problems

Most problems detected during drilling operations occur when tripping out of the well (Cordoso et al. 1995). Real time monitoring of torque and drag have been done for a long time in the oil industry. Pre-calculated HKL data are compared to the measured HKL data where any discrepancies reflects changed hole conditions. The altered hole conditions may be cuttings accumulation, washout, swelling wellbore, key set, dog leg etc.

This chapter will start by presenting how the Knowledge Model are applied to solve drilling problems by analysis of RTDD and other drilling data. The four different groups of mechanical restrictions are presented in the rest of the chapter. Examples of how symptoms of the different restrictions may be used to detect each restriction, will be given, to provide a better understanding when the field data are analysed.

3.1 Failure Cause Determined through Knowledge Modelling

The Knowledge Model, as described in Chapter 2, will be used to determine the failure cause of the restriction events. The input for the KM is symptoms found by studying RTDD from the evaluated restriction event. A symptom is recognized by everything that deviates from the normal or expected value, which is when the drilling process moves from normal state to error state. Example of a symptom is "Excessive Cuttings And Cavings", which is when more cuttings than expected are produced.

When the drilling operation is running as planned, it is in normal state. A symptom signals that the operation moves into error state. Errors may heal themselves, or preventing measures have to be taken to repair or treat the error. "Excessive Cuttings And Cavings" may be caused by "Unstable Formation" and result in the error "Enlarged Wellbore", which is the error subclass of "Reactive Fm.".

If the error is not taken seriously it may lead to a failure. Failures are serious events that have to be repaired in order to continue the operation and get the situation back to normal (Skalle 2011). The error "Enlarged Wellbore" may result in the failure "Accidental Sidetrack" if preventing measures not are taken.

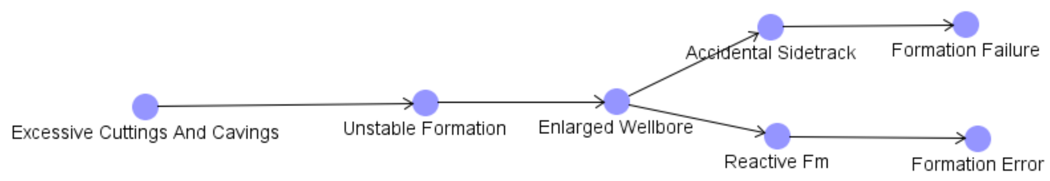

FIGURE 3.1: Example of a symptom resulting in the failure "Accidental Sidetrack"

A simplified version of the KM will be used to determine the cause of the restrictions. The simplification involves including less relationships when the symptoms and the symbolic concepts are related to each other. The simplification is done due to the investigators lack of experience with the model; additional relationships would make the analysis more confusing than more comprehensive. The three following relationships will be used for the analysis:

causes: 0,9

implies: 0,7

involves: 0,5

As mentioned in Chapter 2.2, the explanatory strength will be calculated from the path strengths. The explanatory strength of the highest value represents the main cause of the restriction.

As mentioned above, symptoms are recognized when any deviations from normal are seen during the drilling operation. To give a better understanding of how a symptom is found, the next section describes some important symptoms.

3.1.1 Example of symptoms

Overpull Straight After Flow Check

Overpull Straight After Flow Check is the scenario when the HKL suddenly increases and the string is either stuck or have to be worked free, straight after flow check. If very high overpull is observed straight after flow check, as is the case of one of the restriction events, most likely the string is differential stuck. When the well is flow checked, all operations such as tripping, drilling, circulation and rotation are stopped and the well is observed to see if the well is static or not. In this period, when the string is stationary and usually placed over a permeable formation, the filter-cake may grow and eventually come in contact with the drill string. The result is differential sticking (Azar 2006).

Hard Stringers

Hard stringers may be recognized during the drilling operations as changes in ROP; ROP decreases when hard formation are drilled. The hard stringers are typically interbedded in softer formations which often consist of shale. Soft shale formations may react with the water from the drilling fluid and become weakened and eroded. Enlargements may then develop in the soft formation while the hard stringers remain at their original shape. Wellbore shoulders and ledges are then created at the edge of the hard stringer causing spots where the drill string may get stuck (Skalle et al. 2013).

Shallow Depth

At shallow depths (<2500 m), the formations are less compact and the montmorillonite content in shale is high. Diagnesis has not yet transferred montmorillonite into the less reactive illite and the clay porosity is still high. If water from the drilling fluid reacts with the shale formation, it may start to swell and either collapse into the wellbore or tighten around the drill string. Clay balls may be seen over the shaker, and bit balling may occur (Skalle 2011).

Wellbore Inclination > 30 Degree

Cuttings may start to accumulate on the lower side of the wellbore when the inclination exceeds 30 degree. The cuttings will accumulate into cuttings bed which will start to avalanche when they reach sufficient height. Avalanches occur from wellbore inclination 30-65 degree. At 65 degree, the cuttings will be stationary and will only be lifted from the lower side of the wellbore by pipe rotation. If the cuttings have accumulated in parts of the wellbore, they may create restrictions during tripping. The restrictions may be recognized as increasing overpull at the drill string plows through the cuttings and drags them along (K&M-Technology 2003).

Drill String Vibrations

Drill string vibrations will cause erosion of the wellbore and create hole enlargements. Mechanical erosion results from drill string vibrations due to erosion caused by the BHA, such as the stabilizer or the roller reamer which often has the same OD as the bit. When vibrations occur, the BHA components will hit the wellbore wall and cause pieces of it to break off and fall into the wellbore (Osisanya 2011).

3.2 Wellbore Restrictions and Their Causes

Hook load restrictions are often hard to separate from each other when different symptoms appear at the surface. One of the goals of this thesis is to separate the symptoms of each restriction from each other, to make it possible to reveal the cause of different HKL restrictions at the surface. The following sections will present four main groups of HKL restrictions in order to find unique features of each cause. Symptoms and characteristics of each restrictions cause will be collected as the section is written and used as input for table B.1 – B.4 in Appeindix B, which are created as the analysis is performed. The tables are further discussed in Chapter 4.2.

Hook load restrictions are divided into four main groups:

1. Cuttings Accumulating
2. Mechanically Unstable Wellbore
3. Chemical Unstable Wellbore

4. Other

    - Local Dogleg

3.2.1 Cuttings Accumulation

In this section, the most important causes of cuttings accumulation will be revealed. The group cuttings accumulation have be separated into including cuttings accumulating in straight wellbores, in washouts, and increasing filtercake resulting in differential sticking. The section will start by presenting important characteristics, symptoms and relations of the restriction group, before they are summarized and put in context with the knowledge model at the end of the section.

Cuttings Accumulating in Straight Wellbores

Cuttings plowing during tripping results mainly from poor hole cleaning. Hole cleaning is an important part of the drilling process and involves removal of all drilled out material. Even though a lot of time is spent on hole cleaning, both during the drilling operation and continuously on research of how to increase the cleaning efficiency, it is still one of the most frequent problems during drilling (Shokouhi et al. 2009).

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 (Mohammadsalehi and Malekzadeh 2011). With increased wellbore inclination come increased hole cleaning problems. The hole cleaning efficiency depends on the well angle as the cuttings behave differently at different angles. The well angles may be divided into three groups: 0^o - 30^o, 30^o - 65^o and more than 65^o, where the major problems start when the angle exceeds 30^0 (K&M-Technology 2011). This is illustrated in figure 3.2.

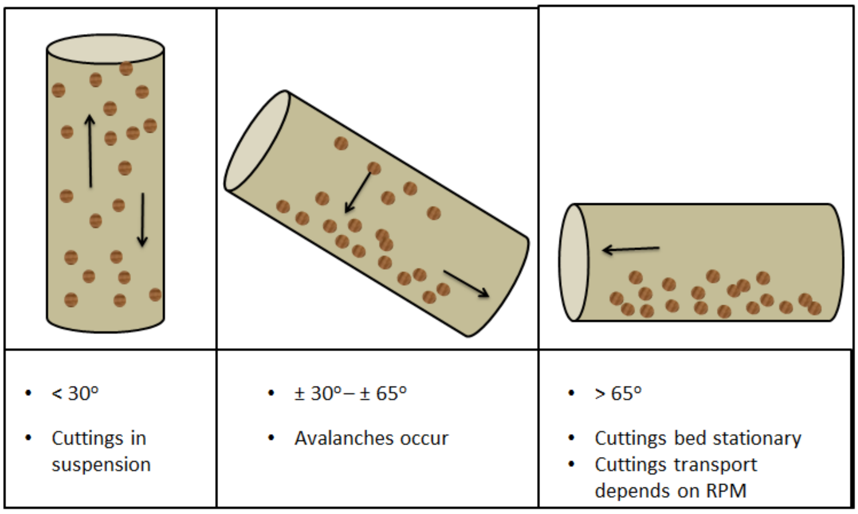

FIGURE 3.2: Cuttings transport depends on the wellbore inclination, free after K & M Technology (2011)

K & M Technology Group (2011) compared cuttings transport out of the well to a conveyor belt, this can be seen in figure 3.3. The lower part of the well will be where the cuttings accumulate. The cuttings are lifted into the high-velocity area in the upper part of the wellbore when the pipe is rotated and fall down into the lower part off the wellbore when the rotation is stopped or decreased. The rotation speed, RPM (rotation per minute), determines the amount of cuttings lifted into the high-velocity area and is different for different hole sizes;

Hole Size	**RPM**
≥ 9" *hole*	>120 RPM
$\leq 8,5$" *hole*	>70 RPM

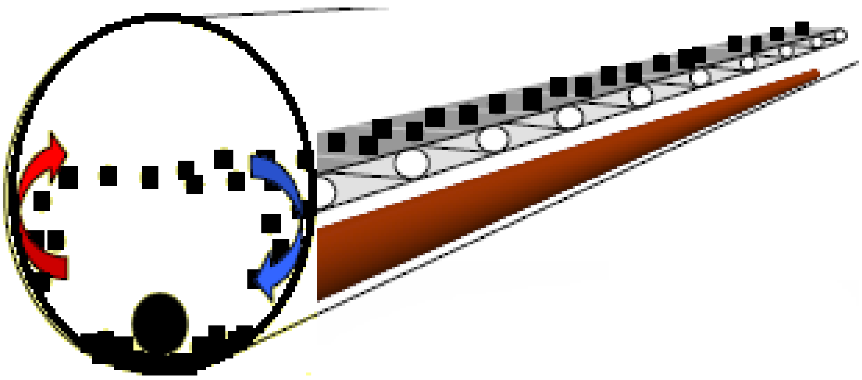

FIGURE 3.3: Cuttings transported on the conveyor belt (K&M-Technology 2011)

The cuttings that are not transported out of the well will start to accumulate into cuttings bed. The cuttings bed will grow until an equilibrium height is reached. At equilibrium height, the cuttings bed will consist of a static layer at the bottom overlaid by a top layer. The static layer will always be present in the wellbore, while the size of the top layer depends on the pipe rotation (K&M-Technology 2011).

Cuttings bed will always be present in a high angle wellbore. The size of the cuttings bed determine whether restrictions will occur during the operation, or if the operation will be trouble free. During tripping operations, the BHA is pulled into the cuttings bed which causes increased hook load (Skalle 2011). When the bottomhole assembly (BHA) is moved axially it will scrape the cuttings into piles, creating plugs of cuttings. The plugs can create restrictions which can lead to high overpull and pack off. This scenario will create a need for repair actions such as backreaming, wiper trips and reduced ROP (Shokouhi, S.V et al. 2009).

Table 3.1 are created based on the information above and are part of table B.1 in Appendix B. The table will continue to grow to include additional symptoms and relationship as the field data are evaluated. The path strength is calculated by equation (2.1). The paths are illustrated graphically by the CREEK tool in figure 3.4.

Table 3.1: Symptoms, error and failure resulting from Cuttings Accumulating

Symptom	**Relation**	**Path Stength**	**Error**	**Failure**
Overpull At Wellbore Inc. > 30 Degree	0,9	0,9		
Low RPM > 9" Hole	0,9 · 0,7	0,63	Accumulated Solids	Hole Cleaning Operation
Less Cutt. On Shaker	0,9 · 0,9	0,81		
Less Cutt. On Shaker	0,5 · 0,7	0,35		
Increased Torque	0,9 · 0,7	0,63		
Increased SPP	0,7 · 0,7	0,49		

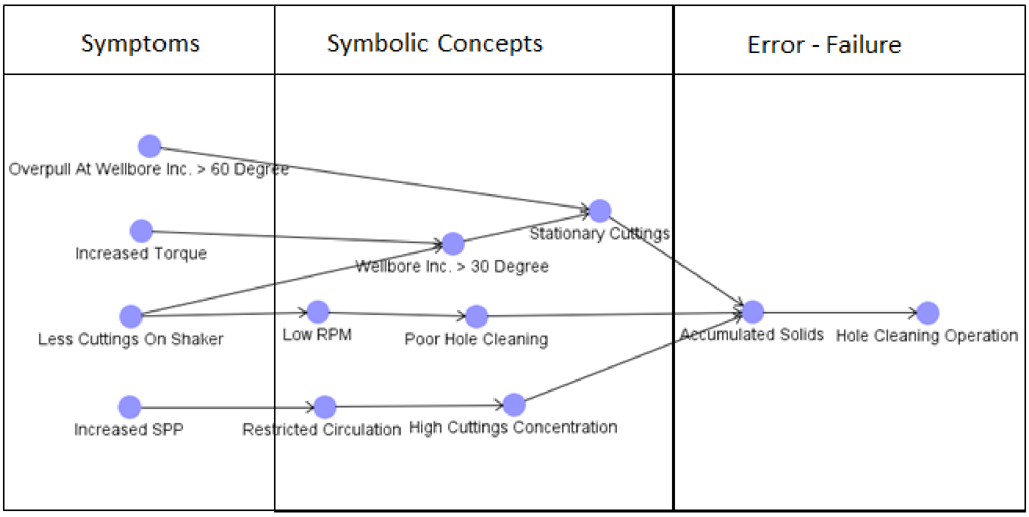

FIGURE 3.4: Symptoms of accumulating cuttings and the resulting error and failure

Restrictions due to Washout

Borehole washout is a hole enlargement in the open hole section created by either borehole breakout or by hydraulically or mechanically erosion of the weak borehole. 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 (Skalle 2011).

Cuttings will be filled into the washout and after long periods of circulation, the bed inside the washout will have become thicker than outside the washout (Skalle 2011). This scenatio is illustrated in figure 3.5 (upper). During tripping out, the BHA will shovel large amounts of cuttings from the washout and into the normal part of the wellbore, creating areas of overpull as illustrated in the lower part of figure 3.5.

Hole enlargement due to borehole breakout and water/shale interaction will be evaluated in the next sections.

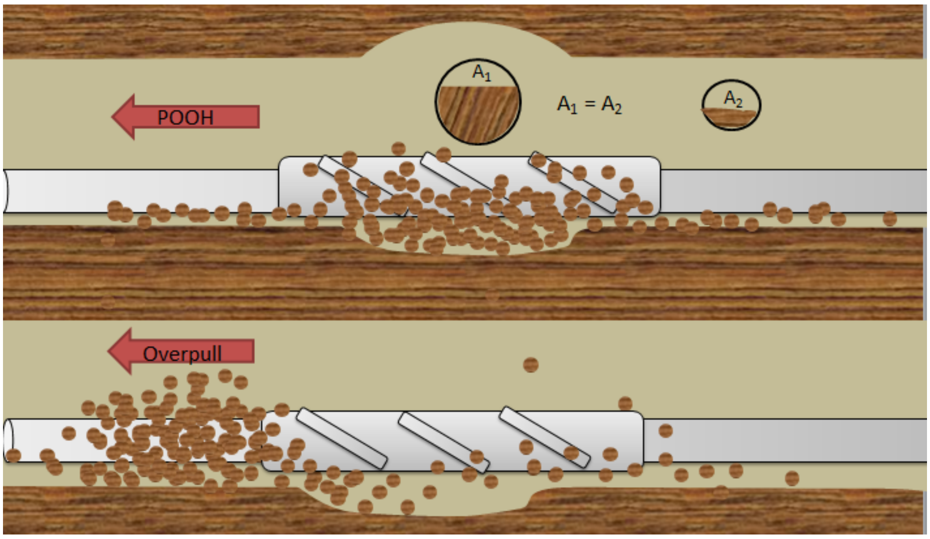

FIGURE 3.5: Overpull due to cuttings accumulating in washouts, free after Skalle (2011)

Washout can create both restrictions due to hole enlargement and due to cuttings accumulating in the washout. This section focuses on the restrictions due to cuttings accumulating. Table 3.2 presents some of the symptoms, the error and failure resulting from wellbore washout.

TABLE 3.2: Symptoms, error and failure resulting from Cuttings Accumulating in Washouts

Symptom	**Relation**	**Path Stength**	**Error**	**Failure**
Difficult Re-Entry Conditions	0,7 · 0,5	0,35		
Excessive Cuttings	0,9	0,9	Accumulated Solids	Hole Cleaning Operation
Enlarge Caliper	0,9	0,9		
Increased Drag	0,7	0,7		
Long Periods Of Circulation	0,7	0,7		

The paths are illustrated graphically by the CREEK tool in figure 3.6.

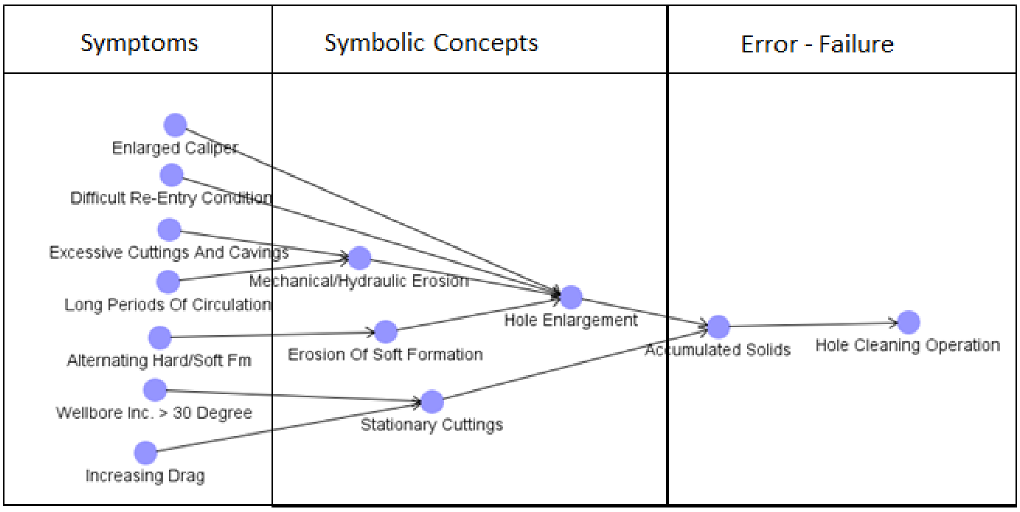

FIGURE 3.6: Symptoms, error and failure resulting from wellbore washout

Differential Sticking

Most permeable formations drilled today are drilled with overbalanced wellbore pressure. One major concern when drilling overbalanced is differential sticking, which is one of the most common causes of stuck pipe (Azar 2006).

Four factors have to be present to cause differential sticking (Drilling-Formulas 2013):

- Permeable formation
- Overbalanced wellbore
- Filtercake
- Stationary pipe

During overbalanced drilling, the pressure in the wellbore balance or exceed the formation pressure, and in that way are the formation fluids prevented from entering the wellbore. This is achieved by choosing a drilling mud that suits the downhole conditions. Since the wellbore is in overbalance, a filter cake will build up in the wellbore. During periods of still stand, when the drill string is placed over a permeable formation, the filter cake may grow and eventually reach contact with the drill string. If the pressure difference, ΔP, between the mud pressure, P_m, acting on the wall of the pipe, is higher than the formation pressure, P_{ff} over a large area, the pipe will become stuck (Azar 2006). This is shown in figure 3.7.

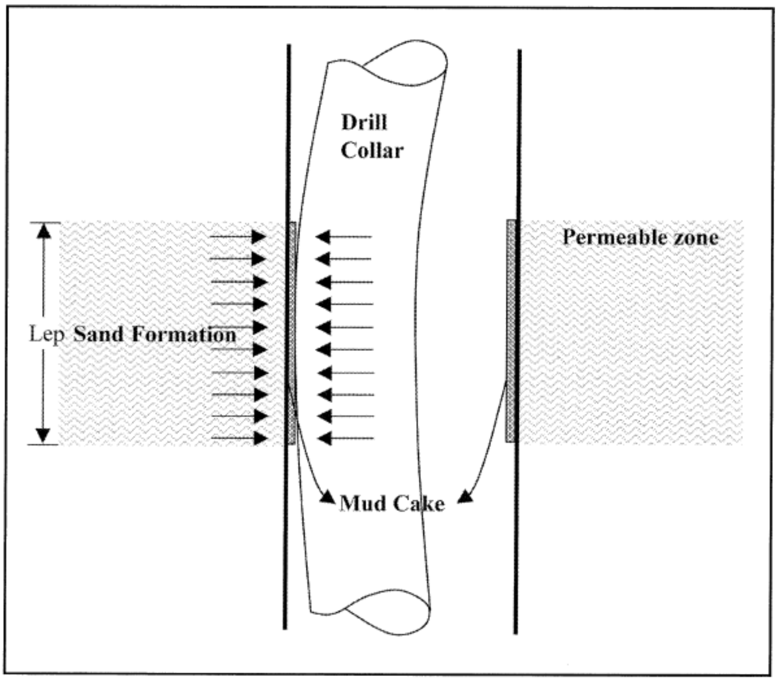

FIGURE 3.7: Drill pipe embedded in the filter-cake due to the pressure difference (Azar 2006)

Table 3.3 presents some of the symptoms, errors and failures resulting from differential sticking. Differential sticking results from the error subclass "Increasing Filtercake", and is thus part of the error "Accumulated Solids". Figure 3.8 presents graphically some symptoms and the resulting error and failure of differential sticking.

TABLE 3.3: Symptoms, error and failure resulting from differential sticking

Symptom	Relation	Path Stength	Error	Failure
Increased Torque	0,9 · 0,9	0,81		
Overpull Straight After Flow Check	0,9	0,9	Accumulated Solids	Hole Cleaning Operation
Unrestr. Ann. Flow	0,7 · 0,9	0,63		

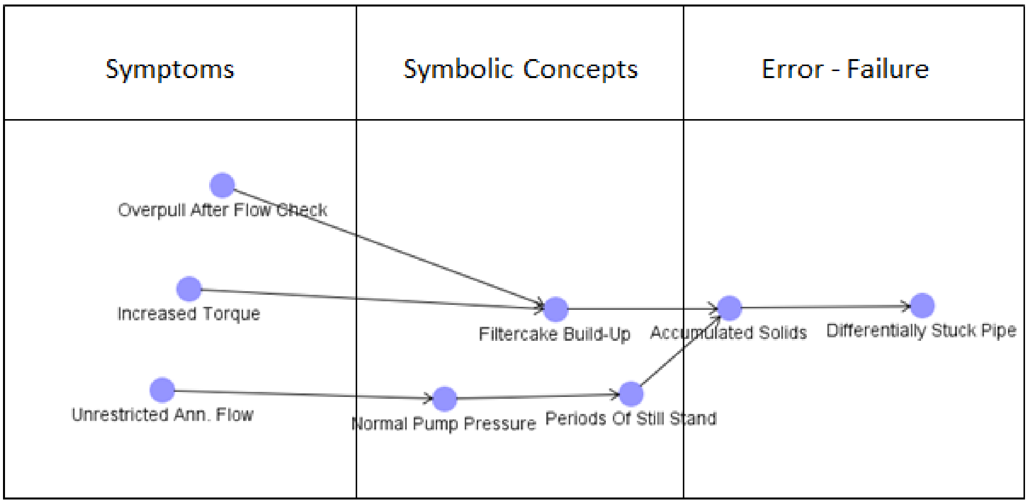

FIGURE 3.8: Symptoms, error and failure resulting from differential sticking

3.2.2 Mechanical Unstable Wellbore

In this section, the causes of mechanical unstable wellbore will be revealed. Different symptoms will be evaluated before they are put in context with the KM and related to different errors and failures.

An unstable wellbore are mainly caused by three different reasons (Azar 2006):

- Mechanical due to in-situ stresses
- Erosion caused by fluid circulation or BHA stress
- Chemical due to reaction between the drilling fluid and the formation

In this thesis, the two first reasons will be evaluated as mechanically unstable wellbore. Mechanical unstable wellbore will be discussed in this section, while the following section will discuss a chemical unstable wellbore.

Unstable Formation

A mechanical unstable wellbore may be identified when there is a difference between the hole diameter compared to the bit size and when the structural integrity of the borehole not are intact. The problem tends to start with creation of fragments (cavings and blocks) from the borehole wall due to mechanical or hydraulic erosion of the wellbore wall (Osisanya 2011). Cavings breaking out from the wall and blocking the wellbore is illustrated in figure 3.9. The cavings tend to be pulled along with the BHA during tripping, which will cause overpull at several spots.

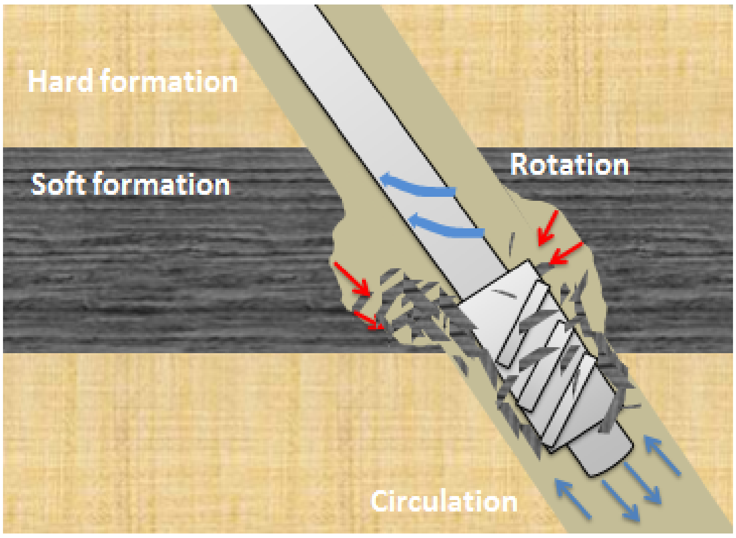

FIGURE 3.9: Wellbore collapse as result of an mechanically unstable wellbore

The wellbore may become unstable for several reasons. If hard formations interbedded in soft and weaker formations are drilled, drill string vibrations may cause fragments of the weak formation to break off and fall into the well, as illustrated in figure 3.10. If hole cleaning is insufficient the fragments may fill the open hole section causing problems such as stuck pipe, pack off, hole collapse, poor hole logging, difficulties when running casing, poor cement jobs and thus increased NPT (Shokouhi et al. 2009).

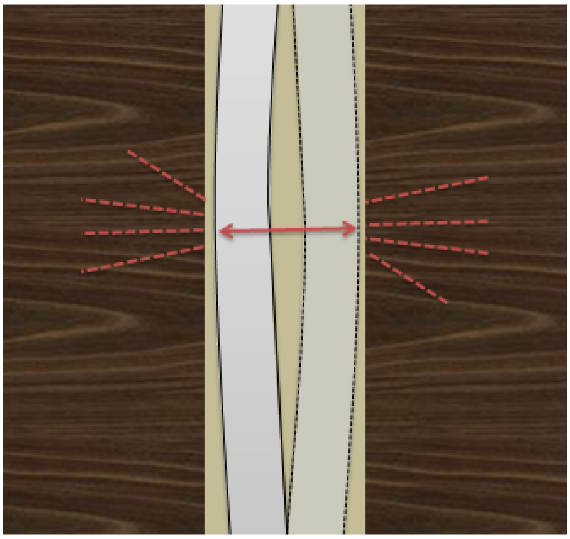

FIGURE 3.10: Wellbore collapse as result of an mechanically unstable wellbore

A formation that has not yet been drilled is in equilibrium state. As soon as the formation is drilled, the stresses are redistributed. The new set of stress is known as wellbore stress. The extent of the wellbore stress depends on the in-situ stress, excessive wellbore pressure or drill string vibrations. When the stress in the wellbore exceeds the formation stress, mechanical instability may occur. If the mud weight is not adjusted to bring the stress to its original state, the formation may become unstable causing blocks and cavings to fall out from the bore hole wall. Thorough planning and compensating measures have to be taken to minimize the consequences of instability problems during drilling (Osisanya 2011).

If cavings start appearing at surface, the restriction cause may be determined by analysing the cavings shape and rate (Osisanya 2011). The cavings type, shape and what their potential origin can be seen in table 3.4. The shape of each cavings type can be seen in figure 3.11.

TABLE 3.4: Overview of the different types of cavings, their shape and what they result from in addition to preventing measures (Osisanya 2011)

Cavings Type	**Shape**	**Resulting From**	**Preventing Measures**
Tabular	Flat and parallel faces from natural fractures or weak planes	Bedding plane failures or fracturing of pre-existing fractures	Improve fluid loss and reduce backreaming and surge/swab
Angular	Curved faces from borehole breakout	Caused by increased stress regime (increased MW)	Optimize trajectory to prevent increased damages
Splintered	Flat, thin and planar from over-pressured zones	UBD through shale with low permeability.	Increase MW and reduce ROP while monitoring ECD

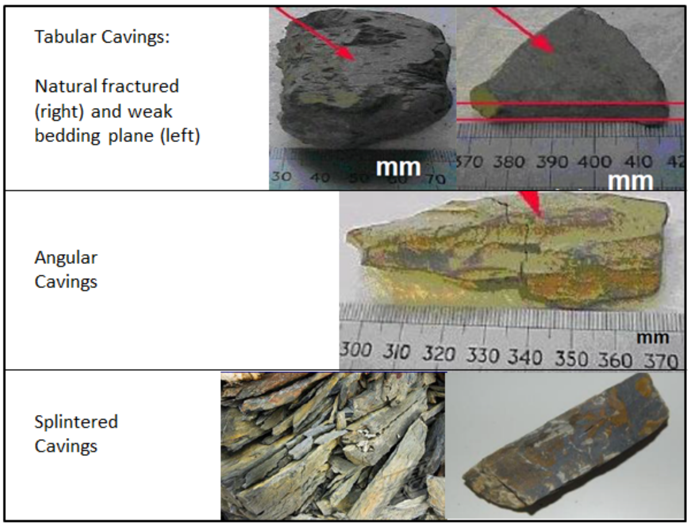

FIGURE 3.11: Geometry shape of each cavings type, free after Osisanya (2011)

Table 3.5 presents some of the symptoms that may be seen on surface when the formation becomes unstable. As seen from the table, the resulting error of mechanically unstable wellbore are Reactive Fm. Reactive Fm. may be caused both mechanically and hydraulically, as was defined as one of the reasons for mechanically unstable wellbore.

TABLE 3.5: Symptoms, error and failure resulting from unstable formation

Symptom	Relation	Path Stength	Error	Failure
Excessive Cuttings/Cavings	0,9	0,9		
Drill String Vibrations	$0{,}7 \cdot 0{,}9$	0,63		
Pack Off After Incr. Rotation And Circulation Stress	$0{,}9 \cdot 0{,}9$	0,81	Rective Formation	Hole Cleaning Operation
Increased Drag	$0{,}5 \cdot 0{,}9$	0,45		

The symptoms, symbolic concepts and the resulting error and failure of unstable formation, are presented graphically in figure 3.12.

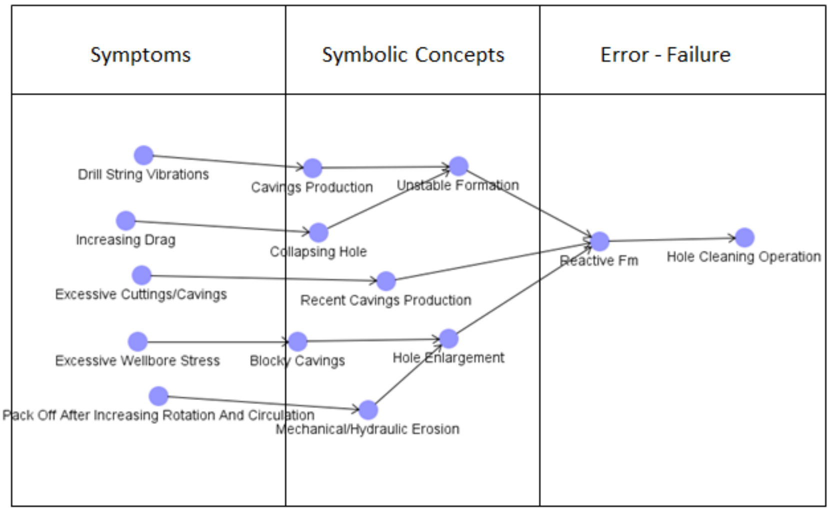

Figure 3.12: Symptoms, error and failure resulting from unstable formation

Ledges

The borehole wall often consists of interbedded soft and hard layers. During drilling, the soft formation may react with the drilling fluid and become mechanically eroded by the BHA and/or hydraulically eroded during long periods of circulation. If the hard formation remains unchanged, an enlarged section of the hole in the soft formation will form and a sharp ledge or shoulder in the hard formation. The hole enlargement may be filled with cuttings while the ledge at the intersection between the soft and the hard formation will create restrictions when tripping (Skalle 2011). Whether the ledge will cause restrictions during tripping in or out depends on its shape. Figure 3.13 illustrates the restrictions created in the wellbore due to ledges.

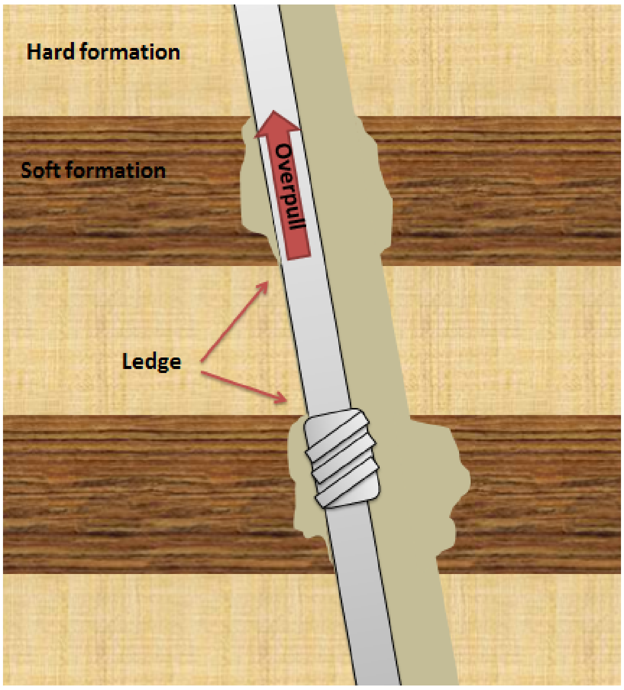

FIGURE 3.13: Ledges created between soft and hard formations creating restrictions during tripping

Table 3.6 presents some of the symptoms and the resulting error and failure that may occur due to ledges.

TABLE 3.6: Symptoms, error and failure resulting from ledges

Symptom	**Relation**	**Path Stength**	**Error**	**Failure**
Sudden Increased ROP	0,5 · 0,7 · 0,7	0,25		
Difficult Re-Entry Conditions	0,7 · 0,9	0,63		
Pack Off During Rotation And Circulation	0,9 · 0,9	0,81	Reactive Formation	Hole Cleaning Operation
Excessive Cuttings	0,7 · 0,7	0,49		
Overpull At Area Of Altern. Soft/Hard Fm.	0,7 · 0,7	0,49		
Overpull	0,7	0,7		

Figure 3.14 presents graphically the symptoms, sybolic concepts and the resulting error and failure of ledges.

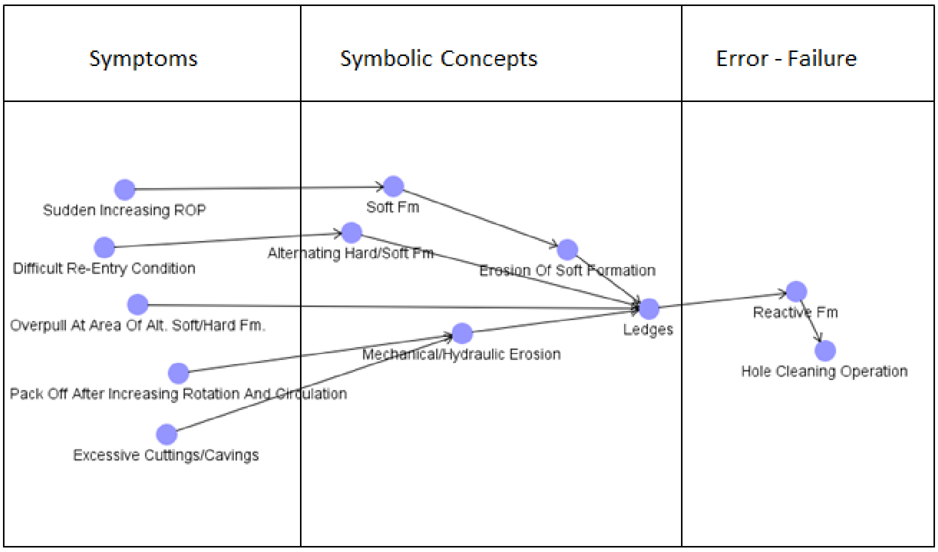

FIGURE 3.14: Symptoms, error and failure resulting from ledges

3.2.3 Chemically Unstable Wellbore

This section will present the most important causes of reactive shale resulting in swelling wellbore. Important characteristics of the restriction cause swelling wellbore will first be presented, before they are put in context with the Knowledge Model.

Swelling Wellbore

The fact that more than 75 % of all drilled formations consist of shale increases the risk of unstable wellbore due to shale swelling, and demands carefully planning and evaluation before each section is drilled and circulated. However, shale instability is still the reason for more than 70 % of all wellbore problems. Reaction between shale and the drilling fluid may lead to a chemical unstable wellbore which may cause the shale to swell and weaken. If preventing measures are not taken, the formation may collapse or the shale may become plastically and flow into the wellbore (Osisanya 2011). Figure 3.15 illustrates the scenario when shale reacts and swells after absorbing fluid from the mud.

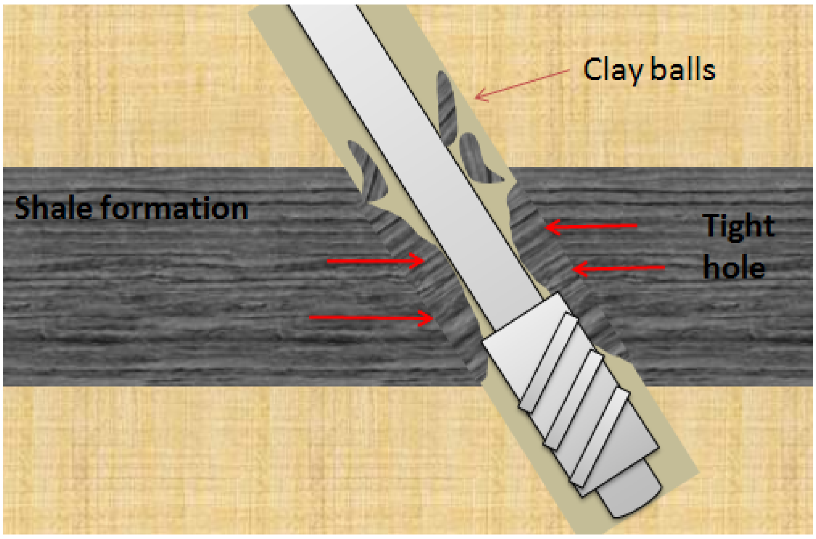

FIGURE 3.15: Reaction between shale and drilling fluid may cause plastically flow into the wellbore

To maintain a stable wellbore, it is important to have knowledge about the shale properties when the correct drilling fluid is selected. The properties include water- and clay content, clay porosity, formation compaction, strength and in-situ stresses (Moody and Hale 1993). The components of the drilling fluid have to be adjusted to fit the current shale properties and thus prevent unwanted reactions between the fluid and the rock components in addition to excess fluid invasion.

The salinity of the mud is one of the most important properties when it comes to reducing the ability to react with shale. When the difference in salinity, ΔA_w, between the pore water and the mud is equal to 0, no osmotic flow will occur and thus no swelling (Skalle 2011).

Clay particles are small crystals that have a weak negative charge. Shale hydration occurs when positive charged water molecules make their way in-between the unit layers due to their attraction to the negative charged clay minerals. The water/shale interaction causes the unit layers to spread. The extent of the swelling is depending on the shale minerals cation exchange capacity. The cations will exchange each other, depending on the concentration of each of them, in the following order: $\mathrm{Al}^{3+} > Mg^{2+} > Ca^{2+} > H^{+} > K^{+} > Na^{+}(Skalle$ 2011).

Montmorillonite is Smectite shale that reacts strongly with water and is thus good for illustration of shale hydration. The content of montmorillonite in shale is therefore one of the main factors involved to determine the shales ability swell. Figure 3.16 illustrates hydration of calcium montmorillonite (upper) and sodium montmorillonite (lower). As can be seen from the figure, sodium montmorillonite will reach strongly with water and swell more than calcium montmorillonite. The reason is that sodium's cation exchange capacity is high compared to calcium's (Skalle 2011).

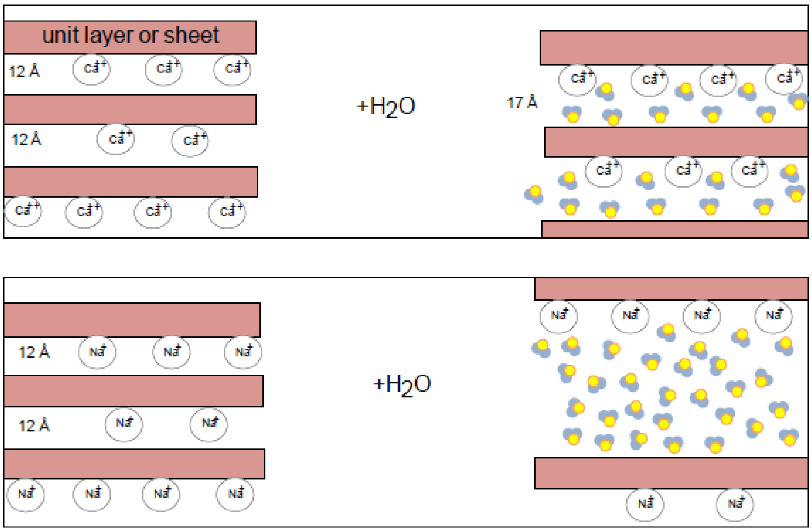

FIGURE 3.16: Hydration of calcium montmorillonite (upper) and sodium montmorillonite (lower) (Skalle 2011)

The water-clay interaction is driven mainly by four mechanisms (Skalle 2011):

- Capillary pressure: Due to the small pore throat of shale formations is the capillary threshold pressure high
- Osmotic pressure: Transfer of water from areas of low salinity to areas of high salinity
- Chemical diffusion (reverse osmosis): Transfer of specific ions from areas of high concentration to areas of low concentration
- Hydraulic pressure difference between mud and shale pore fluid pressure

At shallow depths, the shale is less compact and usually contains more montmorillonite than deeper down. This causes the shale strength at shallow depths to be less than at deeper depths. During osmosis the water will move due to salinity difference causing the shale to become sticky and soft. The swelled shale will be scraped off by the stabilizer and bit and during tripping, and can be seen on surface. At deeper water, more than 2500 m, the shale and clay will have been transferred to illite due to diagnesis. The problems when drilling through shale will then become more related to mechanical stress (Skalle 2011).

Some of the symptoms and resulting error and failure of swelling wellbore are presented in table 3.7, and is presented graphically by the CREEK tool in figure 3.17.

Table 3.7: Symptoms, error and failure resulting from swelling wellbore

Symptom	Relation	Path Stength	Error	Failure
Gumbo Shale Produced	0,9	0,9		
Drilling With WBM	0,5 · 0,7	0,35		
Bit Balling	0,9 · 0,9	0,81	Reactive Formation	Stuck Pipe
Overpull At Shallow Depth	0,5 · 0,9	0,45		
Increased SPP	0,7 · 0,9	0,63		
Difficult Re-Entry Conditions	0,5 · 0,5	0,25		

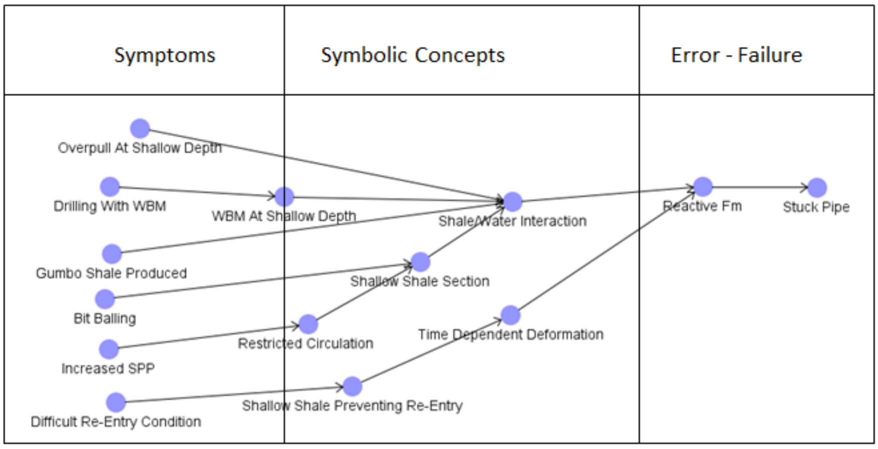

Figure 3.17: Symptoms, error and failure resulting from swelling wellbore

3.2.4 Other Restriction Causes

This section will present the most important characteristics of local dogleg in order to discover symptoms and relations leading to local dogleg. At the end of the section, some of the symptoms and their relations will be put in context with the Knowledge Model.

Local Dogleg

During drilling of a directional well, doglegs are necessary, but have to be controlled in order to reach the desired target. A dogleg results from a sudden change in the wellbore trajectory that leads to a sharper change in the direction of the wellbore than intended. The dogleg severity (DLS) is a function of change in inclination and/or azimuth, expressed as degree/30 m. Severe doglegs do not directly cause any problems, but may cause several drilling, completion and logging problems: (Azar 2006):

- Actual wellbore path to deviate from the planned path
- Difficulties when RIH with casing and increased casing wear
- Key seat
- Casing wear
- Extra time spent on logging
- Poor cement bond in dogleg area
- Problems to set production packer

The risk of dogleg increases in areas consisting of alternating hard and soft formations. Repeated movement of the drill string at the area of the dogleg may lead to key seat and increased risk of stuck pipe (Drilling-Formulas 2013). A key seat may develop at the contact point between the drill string and the formation if the force created by the drill string on the formation is larger than the formation strength. Sideways movement of the drill string is prevented when the drill string is held in tension and a cavity in the borehole wall is thus created. The BHA may be pulled into one of the cavities during tripping, causing increased drag. As the force of the drill string on the formation increases due to increased dogleg, the key seat increases (Pet-Oil 2013). The scenario of a wellbore with gradually increasing dogleg severity and the result of pulling the BHA through a key seat is shown in figure 3.18.

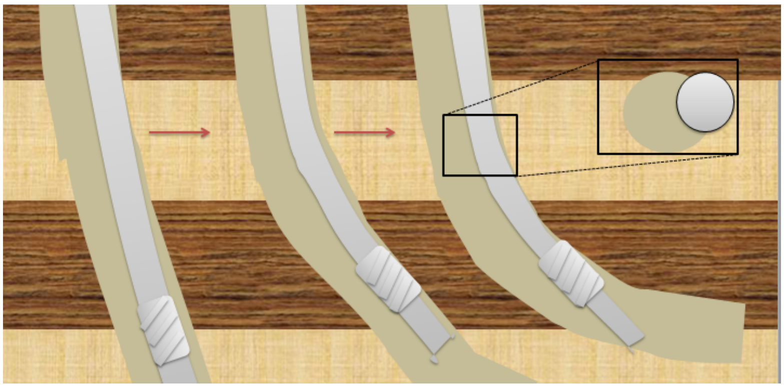

FIGURE 3.18: Gradually increasing wellbore inclination

Table 3.8 presents some symptoms and the resulting error and failure of local dogleg. The symptoms, symbolic concepts and the resulting error and failure are presented graphically in figure 3.19.

TABLE 3.8: Symptoms, error and failure resulting from local dogleg

Symptom	**Relation**	**Path Stength**	**Error**	**Failure**
Difficult Re-Entry Conditions	0,5	0,5		
Increased Drag	0,7	0,7	Crooked	Stuck
High DLS	0,9	0,9	Wellbore	Pipe
Unrestricted Ann. Flow	0,9	0,9		

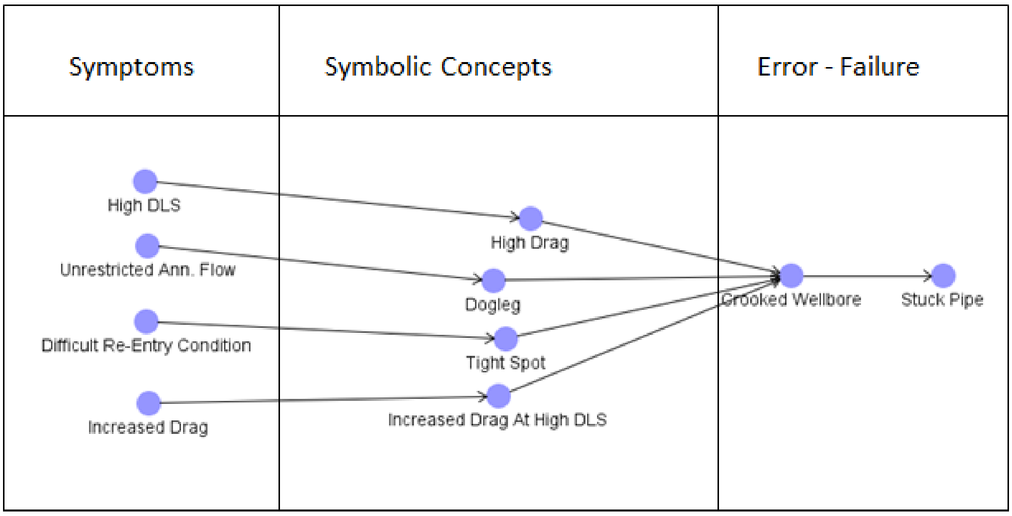

FIGURE 3.19: Symptoms, error and failure resulting from local dogleg

4. Determination of main restriction causes by means of KM

As 50 % of all stuck pipe incidents occur during tripping (Costo et al. 2012), problem detection to reveal the cause of the high percentage is needed. If the correct restriction cause can be determined, the stuck pipe percentage may be reduced. By means of the Knowledge Model, the main cause of several restriction cases will be determined.

The analysis will separate between restriction events and restriction cases. Drilling data from seven different wells were available and included a number of events where HKL restriction had occurred. Out of the available restriction events, five were selected. The five restriction events were selected to create diversity among the restrictions and to include different drilling operations. A summary of the five restriction events can be seen in Appendix A. The five selected restriction events:

1. Gudrun A-12: Drill string parting during tripping after drilling the 17,5" section
2. Gudrun A-12 T2: Sevral spots of overpull during trpping after driling the 17,5" section
3. Gudrun A-5: Cavings production and overpull during drilling of the 17,5" section
4. Snorre B D-3 H: Tight spot at 2200 m
5. Snorre B D-3 H: Running 14" casing

As seen from the list, each event is comprehensive and occur over a long period. For that reason, each event may include several different cases of restriction, which may or may not point to the same restriction case. An example is that the overpull that was observed at Gudrun A-5, may be either due to cavings accumulating in the well, or due to ledges created where the cavings were produced. The analysis will thus start by separating the events and case in order to find additional symptoms and relations. To make the next chapters more understanding for the reader, an overview of how the analyse will be performed are mentioned below:

1. A list of symptoms that may be seen at the surface, and the resulting symbolic concepts and main causes, are made. The list are created to support the analysis when symptoms are recognized from the field data
2. From each restriction event, a large number of restriction cases will be found and analysed by means of the Knowledge Model
3. Analyse the five restriction events entirely to determine the main restriction cause by means of the Knowledge Model

As defined in chapter 3, four main causes of restrictions are investigated. The four main cases are separated into subclasses to make the evaluation more comprehensive. The four main causes and their subclasses will further be referred to as 1a. to 4 c., as can be seen below. Cause 4 b. and 4 c. have not and will not be further discussed in the text, but are included due to their relation to a few symptoms and to make analysis more comprehensive.

1. Cuttings Accumulating
   - a. Cuttings Accumulating in Straight Wellbores
   - b. Cuttings Accumulating in Washouts
   - c. Differential Sticking
2. Mechanically Unstable Wellbore
   - a. Ledges
   - b. Unstable Formation
3. Chemically Unstable Wellbore
   - a. Swelling Wellbore

- b. Washout

4. Others

   - a. Local Dogleg
   - b. Equipment Failure
   - c. Blowout

This chapter will start by shortly presenting the data available for the field analysis and how it was utilized during the analysis. Section 4.2 presents the list of symptoms and how the symptoms are related to different restriction causes. Section 4.3 will describe the cases of restriction and their symptoms, found from the drilling reports and the RTDD. In section 4.4 the HKL signatures that could be seen at surface during each restriction case will be presented and interpreted. The results of the field analysis of the five restriction events are presented in section 4.5.

4.1 Data Available

Historical data from previous drilled wells where HKL restrictions occurred were provided by Statoil. The data includes Daily Drilling Reports, Directional Data and Real-Time Drilling Data. This section will present the data applied for the field analysis. The information available for this analysis was:

- Daily drilling reports:
  - Operation
  - Geological data
  - Drilling fluid
  - BHA details
- Directional Data
- Real-Time Drilling Data

Operational data

Detailed operational data is important for the investigator to get an overview of what happened before, during and after the problem occurred. In addition to describing every part of the operation are also some important discrepancies mentioned. The discrepancies are usually not very detailed described, it is up to the investigator to further analyse what occurred at the depth of interest. An example is when overpull occur at the depth where several hard stringers have been drilled. If the depth of overpull is put in context with the depth of the hard stringers and the BHA component which potentially may get hanged up at the stringers, it may be detected whether the restriction cause was due to ledges (Bjerke 2013).

Geological data

When geological data are included, detailed information about the formations that is being drilled are given. It describes the lithology and the amount of cuttings of each formation. Information about whether limestone stringers or shale formations are present are useful when the restriction cause are being determined. If any geological remarks have been made by the geologist, they are also mentioned in this section and can help understand the restriction cause. An example is if increased amount of cavings or cuttings have been produced. Cavings shape, size and potential origin is presented and gives the investigator the opportunity to further analyse this symptom.

Bit/BHA Data

The BHA data includes an overview of all components of the BHA, their outer diameter (OD), length and the length behind the bit. Information about the OD of the components are, as mentioned under Operational data, important in order to determine whether a spot of overpull was caused by a BHA component getting hanged up at a hard stringer or at hole enlargements. Bit data are important to evaluate whether the bit applied for each section was suited for the downhole conditions.

Drilling Fluid

The drilling fluid data provides information about both the fluid and the equipment. The results of the drilling fluid test are listed and described, which makes it possible to recognize any changes in the drilling fluid composition during the operation. Important information regarding the drilling fluid density and total loss, in addition to any remarks done by the mud engineer, can also be found in the report. One example is the remark that formation water had been sucked into the mud by osmosis. Whether the remark had a meaning for the restriction that occurred later in the well, is thus up to the investigator to determine.

Directional drilling data

The directional drilling data are survey data of the wellbore obtained from Gyros and MWD. The survey includes inclination, azimuth, TVD, navigation and dogleg severity. The data are measured at intervals between 15-20 m, which shrinks to intervals of 5-10 m when important zones are drilled. The directional drilling data are very useful for the investigator when the restriction cause is determined. When the depth of the restriction are found from the operational data, the directional data can reveal whether the restriction occurred at for example high inclination or high dogleg severity, and then make it easier for the investigator to determine the cause of the restriction.

Real-Time Drilling Data

The RTDD includes a graphical description of many of important parameters included in the drilling operation. The most important parameters to be evaluated in this thesis are the HKL signal, the hook height, torque, weight on bit and the bit- and hole- depth. The data will be used when the restrictions are interpreted and the cause of the restrictions are determined. Any discrepancies in the HKL signal are referred to as HKL signature and represents changes in the downhole environment. If the HKL signatures can be related to any downhole restrictions, the restriction cause can be determined at surface.

4.2 Symptoms and Their Potential Target

Table B.1 – B.4 in Appendix B was created to give a overview of the symptoms that may be seen at the surface when a HKL restriction occur and symptoms that can be discovered after the restriction event. The tables have been developed as Chapter 3 was created and as the field analysis has been performed. Whenever new symptoms or relationships are found, they have been included in the table, which makes it a bottom-up approach. By the method of knowledge modelling each symptom have been related to its symbolic concept which either points to the error or to the next symbolic concept.

A symptom may either be characteristic for one restriction cause, or it may indicate several restriction causes. By means of knowledge modelling, the numerical value, presenting the path strength of each symptom, have been calculated, which makes it possible to detect how strongly each symptom points towards each restriction cause.

The tables have been used as support during the field analysis. Any symptoms and relationships recognized and interpreted from the drilling data can be found in the list and used as input for the model.

To be able so separate between the symptoms that are possible to see as the restriction occur and the symptoms that can be seen after the restriction, the symptoms have been categorised to belong in one of the following groups:

1. Measurable symptom ($*$)
2. Not yet measurable symptom ($**$)
3. Future group ($***$)

The measurable symptoms are marked with $*$, and represents the symptoms that can be measured and recognized at the surface during the operation. Group no.2 marked with $**$, represents the symptoms that not yet can be measured at the surface. An example is "Cuttings/Cavings Plowing". This is the symptoms that are included in the analysis of the restriction when the solution are determined. The third group, which is marked with $***$, represents the future group of symptoms. The symptoms are specific and created based on symptoms found from the field analysis. The symptoms may also included as symbolic concepts in the symptoms of group no.1. An example is "Cuttings Storage Tanks Unavailable", which occurred during the same time as increasing cuttings and cavings were produced on Gudrun A-5, and probably resulted in poor hole cleaning.

The tables include some symptoms that are referred to as for example "Low RPM" or "Low Flow Rate". The definitions can be seen in Appendix B.5 and are obtained from the Creek system.

4.3 Cases of Restrictions

21 cases of HKL restrictions were discovered and will be further analysed. The 21 cases and a short description are presented in table 4.1.

Table 4.1: Cases of HKL-restrictions

Case	HKL-Restriction	Description
1	Overpull at 60 degree wellbore inclination	Cuttings are stationary at this angle
2	90 ton overpull straight after flow check	Filtercake may build-up when the drill string is stationary
3	Took Weight at 2810 m	Tight spot observed at wellbore inc. 60 degree
4	Took weight twice at same depth (2750 m)	Took weight at area of hard stringers
5	Several spots of OP from 3084 – 3070 m	Hard stringers drilled in this area
6	Unable to pass 3132 m	Worked through area of hard stringers
7	Several tight spots from 3050 - 3084 m	Worked and washed through area of hard stringers
8	Not able to pass at 3124 m	Circulated while reciprocating passed hard stringers
9	Took weight at 1549 m	Washed and work string passed area of hard stringers
10	Unable to pass tight spot from 3191 – 3144 m	Worked string through area of hard stringers
11	Well packed off during cleaning of well	Huge amounts of cuttings seen over shaker
12	Overpull moving upwards in the well	OP at several depths after recent cavings prod.
13	Tight spot at 1304 m	Mechanically prod. cutt. and cav. when working passed area
14	25 ton overpull at 2392 m	Well packed off at tight spot
15	Took weight while washing down (2772 – 2779 m)	Area of hard stringers
16	Cannot pass tight spot (1177 m)	OP at same spot during tripping
17	Overpull at 1197 m	OP at area of hard stringers
18	Tight spot at 2200 m	Increased drag at area of high DLS
19	Tight spot at wellbore inc. 60 degree (1804 m)	Stationary cuttings may be present
20	Casing stuck at 2048 m	High wellbore inclination
21	Overpull after increased amount of cuttings	Cuttings may accumulate

A number of symptoms were discovered before and during each case. The symptoms that occurred after the case cannot be used to determine the cause of the restriction, but may help in qualifying each case and making it more comprehensive when the analysis is performed.

A symptom that occur at the surface may origin from at least one of the four different restriction groups presented in Chapter 3. Symptoms discovered from the field analysis, are related to the symptoms included in table B.1 – B.4 in Appendix B. The symptoms are picked out and adapted to the current field case; i.e. swelling shale is not mentioned as a restriction cause when the well depth is more than 2500 m, even though it is mentioned as a symbolic concept of the symptom "Overpull After Flow Check". As the symptoms from the field analysis are put in context with the symptoms from the table, step two from Aamodt and Plazas (1994) CBR Cylce are initiated. The symptoms are adjusted to fit the current case, and step three is initiated.

The symptoms could be seen by the drilling crew at the surface and may either have led directly to the restriction case or contributed to the case. Two cases of each restriction event have been put in context with the Knowledge Model and further analysed. The symptoms and to which main cause they are related, are presented in table C.1 in Appendix C. The results of the analysis from the cases of restrictions, are listed in table 4.2. The calculated explanatory strength will thus give an indication of which restriction cause the symptom results from. The path strengths are calculated by equation (2.1) and the explanatory strengths by equation (2.2).

The table presents the main cause of each case, which again have been related to their error group. If the two main restrictions of a case belong to the same error group, they have been added. An example is case 2 where the two main restrictions are Cuttings Accumulating in Washout and Cuttings Plowing in Straight Wellbores. Their collected explanatory strength is 88 %.

The explanatory strength of each restriction cause are found by dividing the path strength of each group by the total path strength, (equation (2.2)). The explanatory strength may be translated into percentage, in order to make it easier to compare them to each other:

$$\frac{Explanatory\ strength\ for\ a\ given\ restriction\ cause \cdot 100}{Total\ explanatory\ strength\ for\ all\ cases} = [\%]$$

TABLE 4.2: Cases and their restriction cause, failure, primary and secondary error

Case	**Main Cause – %**	**Failure**	**Primary Error – %**	**Secondary Error – %**
2	1 c. – 59	Drill String Twist Off	Acc. Solids – 88	Crooked Wellb. – 12
3	1 a. – 49	Hole Cleaning Operation	Acc. Solids – 59	Crooked Wellb. – 20
4	2 a. – 63	Hole Cleaning Operation	Reactive Fm. – 63 .	Crooked Wellb. – 22
7	2 b. – 56	Hole Cleaning Operation	Reactive Fm. – 56	Acc. Solids – 16
12	2 b. – 62	Collapsed Well	Reactive Fm. – 88	Acc. Solids – 12
13	2 b. – 78	Collapsed Well	Reactive Fm. – 100	
16	2 a. – 49	Collapsed Well	Reactive Fm. – 100	
18	4 a. – 56	Hole Cleaning Operation	Crooked Wellb. – 56	Acc. Solids – 44
19	1 a. – 57	Hole Cleaning Operation	Acc. Solids – 57	Crooked Wellb. – 33
21	1 b. – 44	Hole Cleaning Operation	Acc. Solids – 85	Reactive Fm. – 14

4.4 Recognition of HKL Signatures

The HKL data origin from real-time signal obtained from the monitoring systems gathered during tripping operations. The measured data will most of the time display a straight, constant line, indicating a smooth and clear hole. Once in a while deviating curves will be created depending on the conditions in the open hole (Cordoso et al. 1995). The deviations are referred to as HKL signatures and will appear if any restrictions are met during tripping.

During tripping operations, the drill string is held in tension and the hook is taking the full weight of the string, in addition to the friction from the borehole wall.

Cordoso et al. (1995) presented how the borehole friction factor can be applied for borehole diagnosis and thus be used as a method for early recognizing of drilling problems. Type curves from differential sticking was successfully detected.

Table C.2 in Appendix C, presents the HKL signature that could be seen at surface when each at the moment of each case. Case 2, 12, 16, 18 and 19 are further analysed below.

A thorough study of the HKL signatures will not be done in this thesis, however, the signatures will be put in context with the restriction cause determined by the Knowledge Model.

Case 2: 90 ton overpull straight after flow check, Gudrun A-12

Figure 4.1 presents the HKL signature at the time of overpull straight after the well had been flow checked. From the difference between the HKL during overpull and the normal HKL during tripping, it can be seen that the overpull was 90 ton. The normal HKL is presented by the dotted line. Cordoso et al. (1995) have already recognized a characteristic HKL signature of differential sticking. The signature starts with overpull and when the pulling force exceeds the force of differential sticking, the pipe is released and the normal HKL signal can be seen. This is the same characteristics as what can be seen in the HKL signature of case 2.

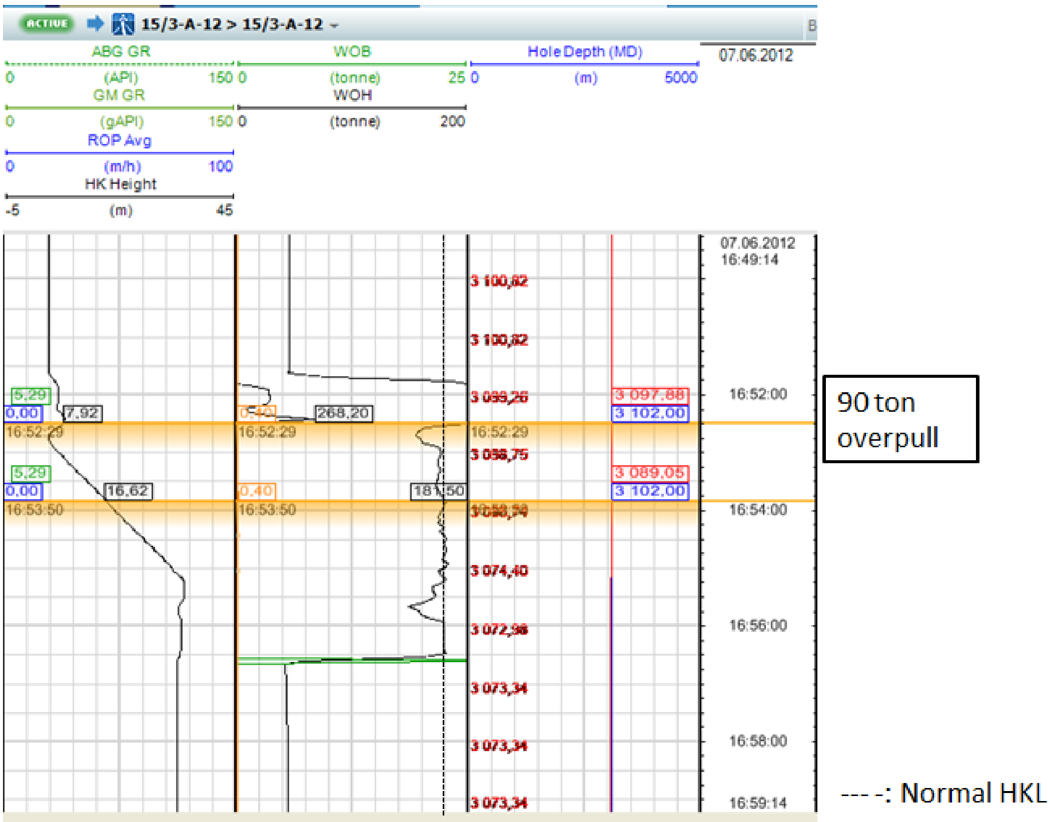

FIGURE 4.1: Case 2: HKL-signature at the moment of 90 ton overpull after flow check, Gudrun A-12

Case 12: Overpull moving upwards in the well, Gudrun A-5

At case 12, it seemed like the spot of overpull was movings upwards in the well. Figure 4.2 presents the HKL-signature seen during tripping after cavings started to appear on surface. As can be seen from the figure, the first spot of overpull was at 1123 m, followed by overpull at 1121 m and 1117 m. The spot of overpull moves slightly upwards in the hole during tripping, indicating that cavings are accumulating in the well and are being plowd along with the BHA during tripping. The signature show a smooth increasing HKL before it suddenly increases to a maximum.

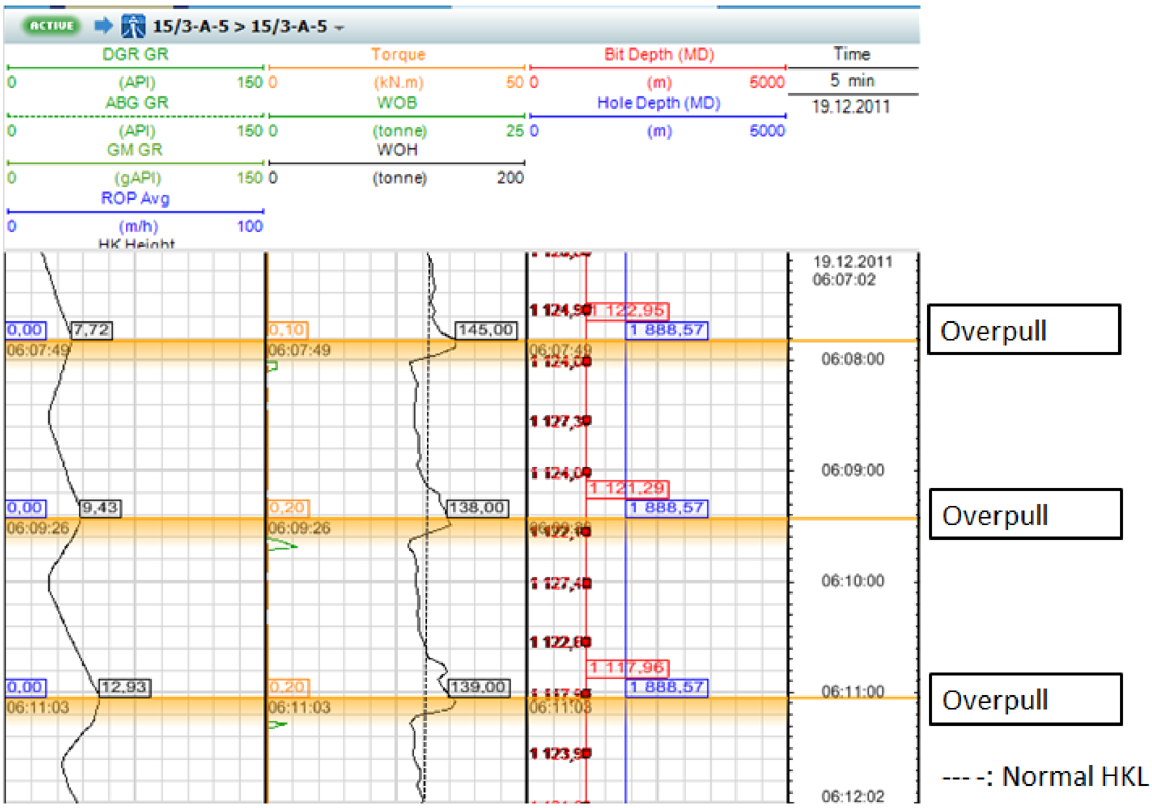

FIGURE 4.2: Case 12: HKL-signature at the restriction from 1122 m – 1128 m

Case 16: Cannot pass tight spot at 1177 m, Gudrun A-5

Figure 4.3 show the HKL-signature at 1177 m, where a restriction was met and had to be worked through. As seen from the HKL signature, there is an increasing overpull as the string is pulled. The increase is probably due to stretch of the pipe. Since maximum overpull occur at the same fixed spot for all cases presented in the figure, the cause of the restriction is most likely one of the BHA components are hanged up at a hard stringer.

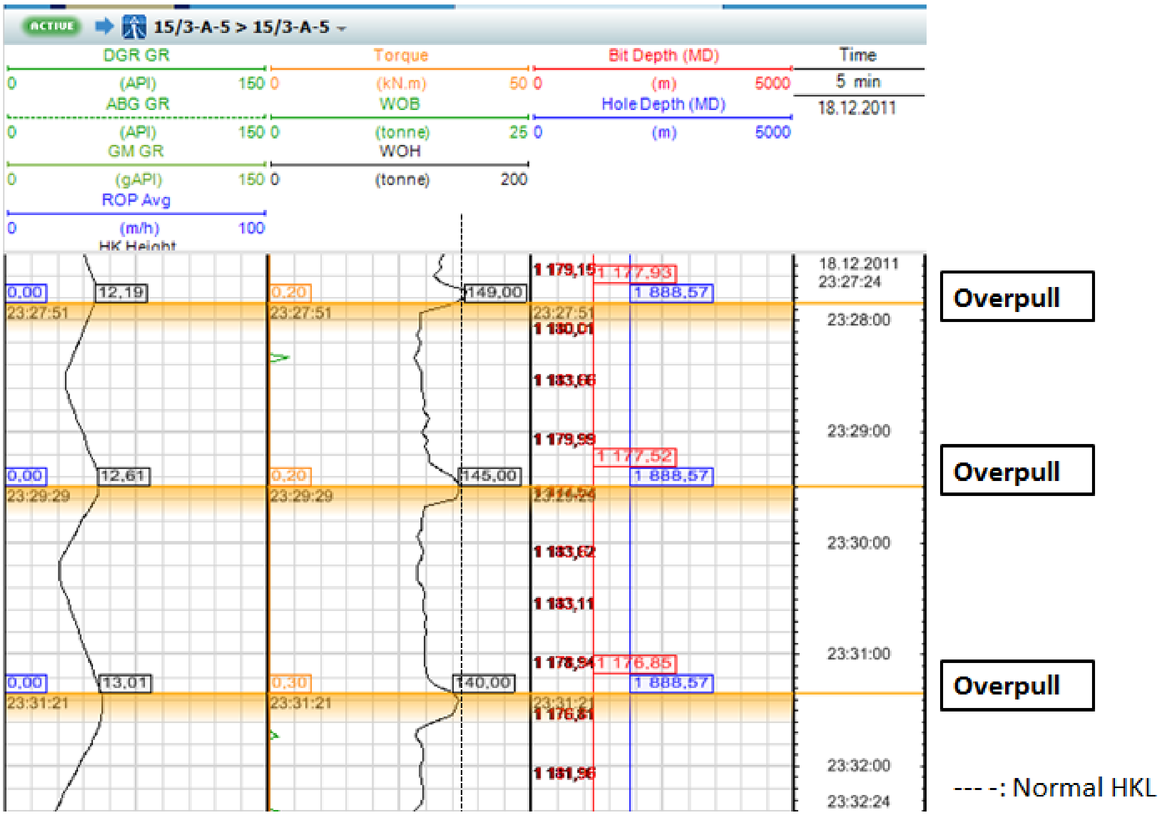

FIGURE 4.3: Case 7: HKL-signature at the restriction at 3053 m

Case 18: Tight spot at high DLS, Snorre B D-3 H

The HKL-signature at the tight spot at 2203 m can be seen in figure 4.4. As seen from the figure, several spots of 20 ton overpull was observed as the string was being worked through the area of high DLS. The HKL signature of this case can be recognized as a sharp build-up at a fixed spot, which is the same as can be seen when the restriction is caused by ledges. When the cause of this restriction are determined, it have to be put in context with symptoms seen earlier in the drilling operation. A tight spot at 2200 m has seen also during the drilling operation, and when the signal is combined with the knowledge of DLS being between 4,5 and 4,0 degree/30 m, it can be assumed that local dogleg caused the restriction.

The uneven signal compared to the signal from Gudrun A-12 and Gudrun A-5 are due to the rig drilling Snorre B D-3 H being semi-submersible and the rig drilling Gudrun A-12 and A-5 are a jack-up.

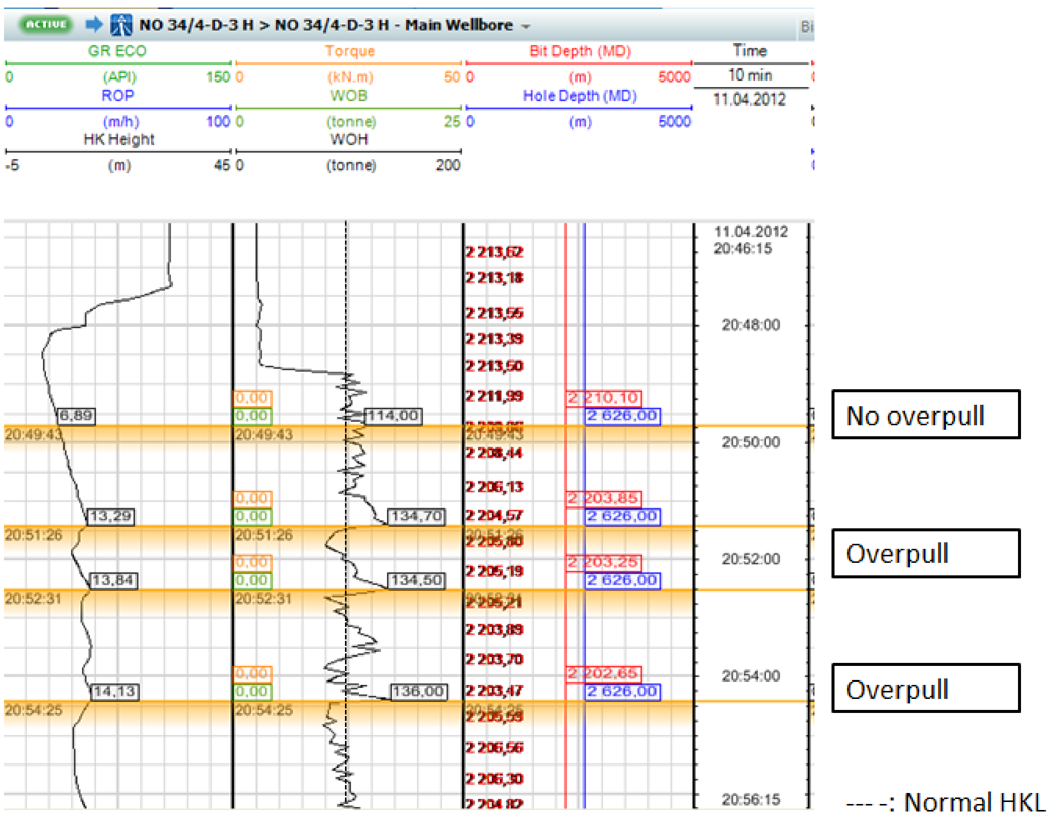

FIGURE 4.4: Case 18: HKL-signature at the tight spot at 2200 m

Case 19: Tight spot at high wellbore inclination, Snorre B D-3

The casing running got restricted by a tight spot at > 60 ^{o} wellbore inclination. Figure 4.5 present the HKL signal of the tight spot at 1747 m, which is when the the casing is being worked upwards after getting stuck at 1804 m. As seen from the signal, the HKL increases slowly as the casing is being pulled, until it reaches a maximum overpull. When the casing is pulled again, the same scenario occur, only this time at a higher point in the wellbore. This indicates that the spot of overpull is moved upwards in the well, probably due to cuttings being plowd along with the BHA.

As for case 18, the HKL signal origins from a semi-submersible rig, which makes is more uneven than for the other cases. Rig heave at the time of the restriction was 2,5 m.

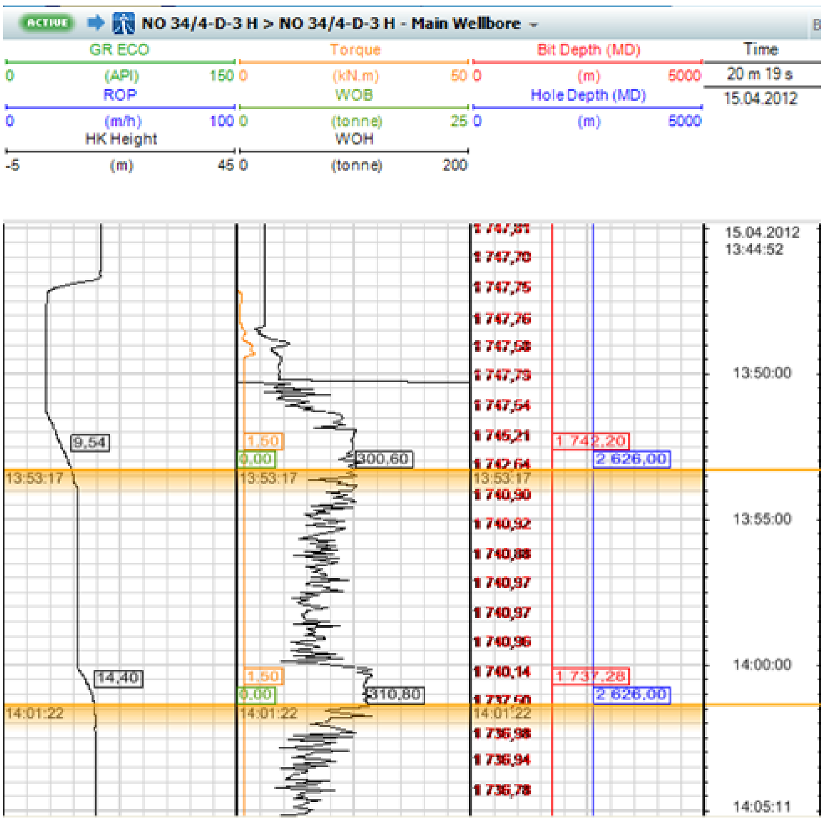

FIGURE 4.5: Case 19: HKL-signature at the restriction at 1804 m

When the HKL signatures are compared, a difference between the HKL signature of cuttings accumulating and ledges/local dogleg can be discovered. The HKL signature that can be seen when cuttings accumulation is the main cause, is characterized by a smooth increasing drag, where the spot of overpull moves upwards in the well during tripping. As for ledges and local dogleg, the spot of overpull is fixed, and a sharp build-up can be seen when the pipe stretch reaches its maximum. This is the same result as master's student Bjerke (2013) has proved in her results where a thorough analysis of HKL signatures have been done.

4.5 Results Field Analysis

The next sections will present how the main restriction cause of each selected event is determined by means of the Knowledge Model.

The analysis starts by calculating the the path strength of each symptom, before the explanatory strength are calculated. As for the analysis of the restriction cases, the path strength are found by equation (2.1) and the explanatory strength by equation (2.2).

Gudrun A-12:Drill string parting during tripping after drilling the 17,5" section

Included in this restriction event, is case 1 – 3. The symptoms of the cases have been collected and analysed together. The results can be seen in table 4.3. The table presents the strength between each symbolic concept and the resulting path strength. Each symptom origins from either one or more main causes. When the path strengths of each main cause are added, the explanatory strength can be found. The sum of the explanatory strengths of all main causes is always equal to 1, so to avoid confusion, the explanatory strength of each main cause has only been mentioned once for each cause. This method of displaying the results is common for all five events.

As seen in table 4.3, the sum of the path strengths of 1 c., differential sticking, are 3,18. The explanatory strength of differential sticking in terms of percent, is then:

$$\frac{3,18 \cdot 100}{6,54} = 49\%$$

Table 4.3: Case 1 – 3, symptoms, path strength and explanatory strength resulting in the main cause differential sticking

Case	Symptom	Strength	Path Strength	Main Cause	Expl. Strength
	OP After Flow Check	0,9	0,9	1 c.	0,49
	Restricted Rotation	0,9 · 0,9	0,81	1 c.	
	Wellbore Inc. > 60 ^{o}	0,7 · 0,5 · 0,9	0,32	1 c.	
	Wellbore Inc. > 60 ^{o}	0,7 · 0,5	0,35	1.a	0,31
1 – 3	Overbalanced Pressure	0,9 · 0,5	0,45	1.c	
	Unrestr. Ann. Flow	0,7 · 0,9	0,63	4 a.	0,10
	Unrestr. Ann. Flow	0,7	0,7	1.c	
	Mud Pumps Down	0,7 · 0,7	0,49	1.a	
	Cav./Cutt. Plowing	0,7	0,7	1.a	
	String Stalled Out	0,7 · 0,7	0,49	1 a.	
	Reaming	0,7	0,7	2 a.	0,11
	Sum		6,54		1.01

From table 4.3, it can be seen that the main cause of the restriction on Gudrun A-12 is differential sticking with explanatory strength of 49 %, and the secondary cause is cuttings accumulation with explanatory strength of 31 %. The main cause differential sticking results in the error subclass Increasing Filtercake and cuttings accumulation results in the subclass Solids Settling. Table 4.4 presents the explanatory strengths of the error subclasses, error groups and failure resulting from the restriction event. Increasing Filtercake and Solids Settling are both subclasses of Accumulated Solids. The explanatory strength of Accumulated Solids is the sum of both its subclasses; 80 %, and is thus the main error of the restriction. The resulting failure is Drill String Twist Off.

Table 4.4: Case 1 – 3, results field analysis, error group, subclass and failure, Gudrun A-12

Error Subclass	Expl. Strength	Error Group	Collected	Failure
Solids Settl.	31 %	Accumulated		
Increasing Filtercake	49 %	Solids	80 %	Drill String
Enlarged Wellbore	11 %	Reactive Fm.	10 %	Twist Off
Dogleg	10 %	Crooked Wellbore	10 %	

The symptoms and their symbolic concept and resulting errors of the drill string twist off failure, are presented graphically by the CREEK tool in figure 4.6. As presented in Chapter 2.2, the relation between symptom and symbolic concept are always equal to 1.0. This relation is not included in table 4.3, and is the reason for why each symptom has one more relation than mentioned in the table.

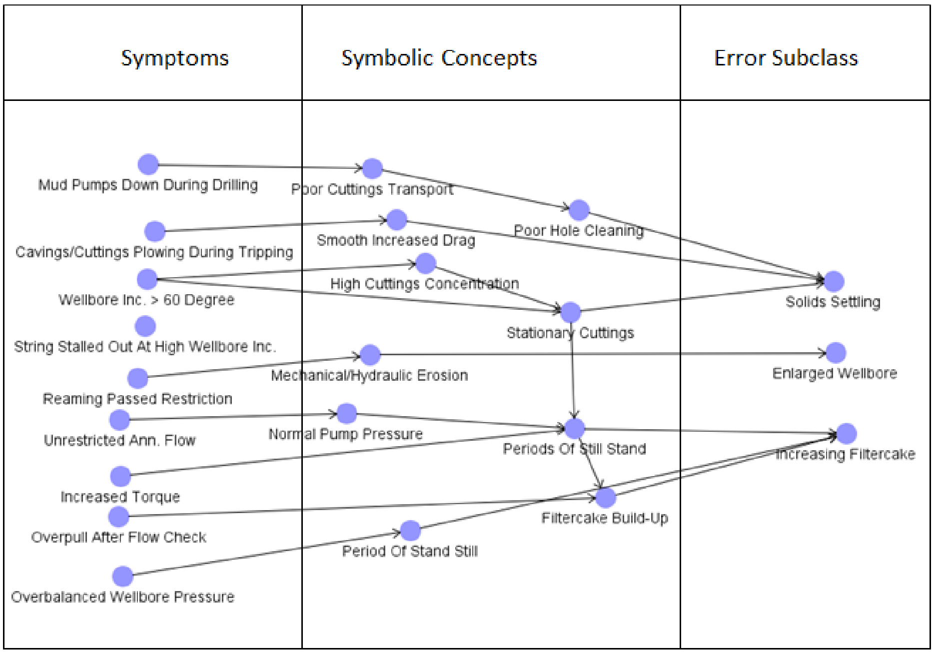

FIGURE 4.6: Results of the field analysis, case 1– 3, Gudrun A-12

Gudrun A-12 T2: Sevral spots of overpull during trpping after driling the 17,5” section

Included in this restriction event, is case 4 – 11. The symptoms of the cases have been collected and analysed together. The results can be seen in table 4.5. The same method of analysing and displaying the results as for Gudrun A-12 has been used for this event.

Table 4.5: Case 4 – 11, symptoms, path strength and explanatory strength resulting in the main cause ledges

Case	Symptom	Strength	Path Strength	Main Cause	Expl. Strength
	Altern. Soft/Hard Fm.	0,5 · 0,9	0,45	2 a.	0,74
	Altern. Soft/Hard Fm.	0,5 · 0,7	0,35	1 b.	0,16
	Altern. Soft/Hard Fm.	0,5 · 0,9	0,35	4 b.	0,10
	Wellbore Inc. > 60 ^{o}	0,7 · 0,5	0,35	1.b	
4 –	Hard Stringers	0,7	0,7	2 a.	
11	Hard Stringers	0,9 · 0,5	0,45	4 b.	
	Unrestr. Ann. Flow	0,7 · 0,7	0,49	2 a.	
	Undergauged BHA Comp.	0,7 · 0,7	0,49	2 a.	
	Drill String Vib.	0,5 · 0,5	0,25	2 a.	
	Reaming Down	0,7 · 0,7	0,49	2 a.	
	Took Weight	0,7 · 0,7 · 0,9	0,44	2 a.	
	Pack Off	0,9 · 0,9	0,81	2 a.	
	Excessive Cutt./Cav.	0,7 · 0,9	0,63	1 b.	
	Excessive Cutt./Cav.	0,7 · 0,7	0,49	2 a.	
	Overpull	0,7 · 0,7	0,49	2 a.	
	Sum		7,72		1.0

From table 4.5 it can be seen that the main cause of the restriction of Gudrun A-12 T2 is ledges with explanatory strength 74 %, and the secondary cause is cuttings accumulating in washouts. The main cause ledges, results in the error subclass Enlarged Wellbore, and while cuttings accumulating in washouts results in the error subclass as Solids Settling. Table 4.6 presents the explanatory strengths of the error subclasses, error groups and the failure resulting from the restriction event. Enlarged Wellbore is the error subclasse of Reactive Fm., which thus is the main error with explanatory strength of 74 %. The failure of the event is Hole Cleaning Operation.

Table 4.6: Case 4 – 11, results field analysis, error group, subclass and failure, Gudrun A-12 T2

Error Subclass	Explanatory Strength	Error Group	Collceted	Failure
Solids Settling	16 %	Acc. Solids	16 %	Hole Cleaning
Enlarged Wellbore	74 %	Reactive Fm.	74 %	Operation
Drill String Failure	10 %	Equip. Failure	10 %	

Figure 4.7 presents graphically the symptoms, their symbolic concepts and the resulting error.

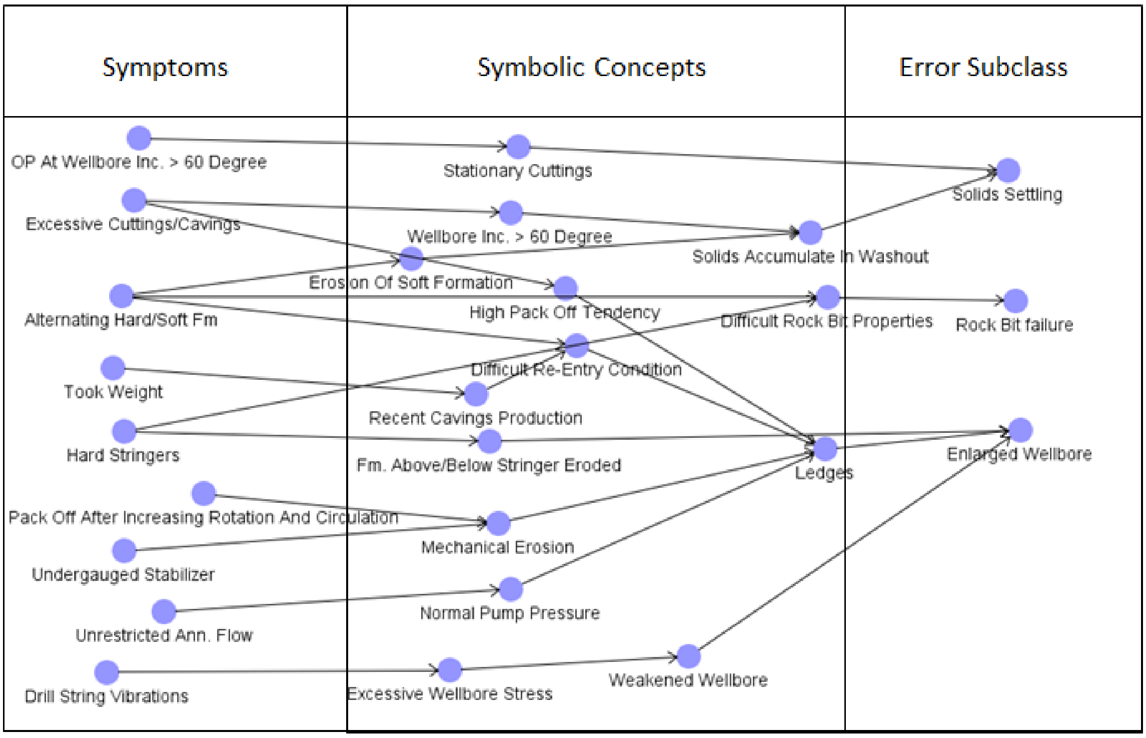

FIGURE 4.7: Results of the field analysis, case 4– 11, Gudrun A-12 T2

Gudrun A-5: Cavings production and overpull during drilling of the 17,5" section

Included in this restriction event, is case 12 – 17. The symptoms of the cases have been collected and analysed together. The results can be seen in table 4.7. The same method of analysing and displaying the results as for the two events above has been used.

Table 4.7: Case 12 – 17, symptoms, path strength and explanatory strength resulting in the main cause unstable formation

Case	Symptom	Strength	Path Strength	Main Cause	Expl. Strength
	Cav./Cutt. Plowing	0,7	0,7	2 b.	0,57
	Cav./Cutt. Plowing	0,7	0,7	1 a.	0,07
	Fm. Fluid/Mud Interact.	0,9	0,9	3	0,19
	Fm. Fluid/Mud Interact.	0,5 · 0,5 · 0,9	0,23	2 b.	
	Shallow Depth	0,9 · 0,9 · 0,7	0,56	3	
	Non-PDC Cuttings	0,9 · 0,5	0,45	2 b.	
12 – 17	OP At Shallow Depth	0,9 · 0,7 · 0,7	0,44	2 b.	
	OP At Shallow Depth	0,7 · 0,9 · 0,7	0,44	3	
	Took Weight	0,5 ·0,9	0,45	2 b.	
	Blocky Cavings	0,9 · 0,9	0,81	2 b.	
	Pack Off After Inc. Rotation And Circ.	0,5	0,5	2 a.	0,17
	Pack Off After Inc. Rotation And Circ.	0,9 · 0,5	0,45	2 b.	
	Excessive Cutt./Cav.	0,9	0,9	2 b.	
	Excessive Cutt./Cav.	0,9 · 0,9	0,81	2 b.	
	Alt. Soft/Hard Fm.	0,5 · 0,9	0,45	2 a.	
	Hard Stringers	0,5 · 0,7	0,35	2 b.	
	Hard Stringers	0,7	0,7	2 a.	
	Sum		9,84		1.0

From table 4.7 it can be seen that the main cause of the restriction of Gudrun A-5 is unstable formation with explanatory strength 57 %, and the secondary cause is swelling wellbore. The main cause unstable formation results in the error subclass Enlarged Wellbore, and swelling wellbore results in the subclass Reactive Shale. Table 4.8 presents the explanatory strengths of the error subclasses, error groups and the failure resulting from the restriction event. Enlarged Wellbore and Swelling Shale are both subclasses of the error of Reactive Fm. The explanatory strength of Reactive Fm. is the sum of both subclasses; 93 %, and is this the main error of the restriction. The resulting failure is Collapsed Well.

Table 4.8: Case 12 – 17, results field analysis, error group, subclass and failure, Gudrun A-5

Error Subclass	Expl.	Error Group	Collceted	Failure
Solids Settling	7 %	Acc. Solids	7 %	Collapsed Well
Enlarged Wellbore	74 %	Reactive Fm.		
Reactive Shale	19 %	Reactive Fm.	93 %	

The symptoms, symbolic concepts and potential resulting errors are presented graphically in figure 4.8.

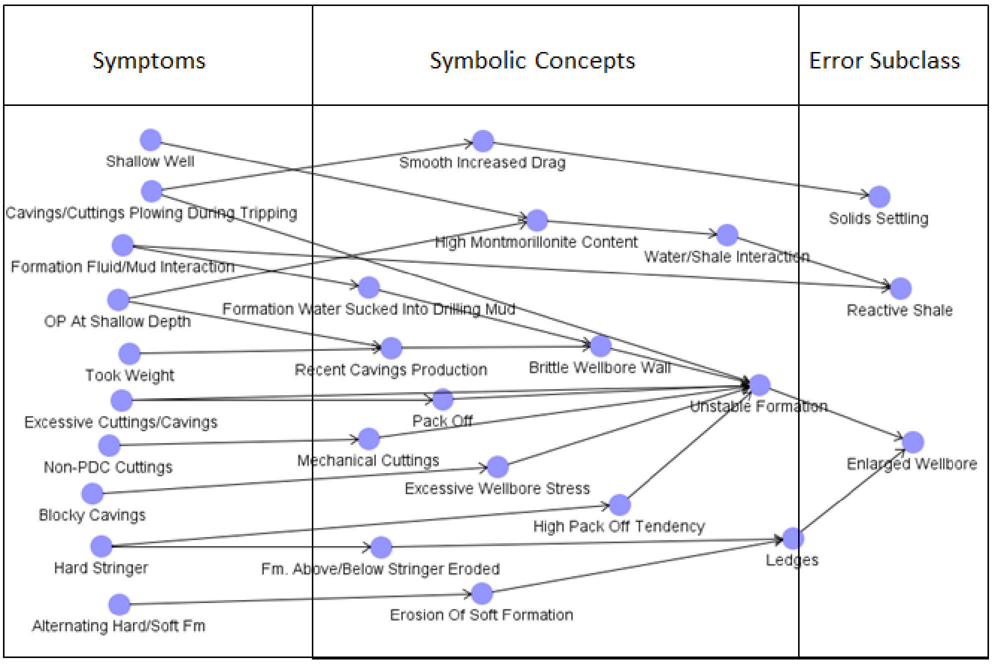

FIGURE 4.8: Results of the field analysis, case 12 – 17, Gudrun A-5

Snorre B D-3 H: Tight spot at 2200 m

Two event was studied on Snorre B D-3 H. Included in this restriction event, is case 18. The symptoms of the cases have been collected and analysed together. The results can be seen in table 4.9. The same method of analysing and displaying the results as for the three events above has been used.

TABLE 4.9: Case 18, symptoms, path strength and explanatory strength resulting in the main cause local dogleg

Case	Symptom	Strength	Path Strength	Main Cause	Expl. Strength
	High DLS	$0,5 \cdot 0,9$	0,45	1 a.	0,28
	Increased Drag	0,7	0,7	4 a.	0,56
	High DLS	0,7	0,7	4 a.	
18	OP At Wellbore Inc. $> 60\,^o$	$0,9 \cdot 0,9$	0,81	1.a	
	OP At Wellbore Inc. $> 60\,^o$	$0,7 \cdot 0,5$	0,35	1.b	0,16
	Alt. Soft/Hard Fm.	0,5	0,5	4 a.	
	Alt. Soft/Hard Fm.	$0,5 \cdot 0,7$	0,35	1 b.	
	Unrestr. Ann. Flow	$0,7 \cdot 0,9$	0,63	4 a.	
	Sum		4,49		1.0

From table 4.9 it can be seen that the main cause of the first restriction event on Snorre B D-3 is local dogleg with explanatory strength 56 %, and the secondary cause is cuttings accumulating. The main cause local dogleg results in the error subclass Dogleg, and cuttings accumulating results in the subclass Solids Settling. Table 4.10 presents the explanatory strengths of the error subclasses, error groups and the failure resulting from the restriction event. Dogleg are the error subclass of Crooked Wellbore, which resulted in explanatory strength of 56 % and is the main error of the restriction. The secondary cause cuttings accumulating and the third cause, are both subclasses of Accumulating Solids, which resulted in explanatory strength of 44 %.

Table 4.10: Case 18, results field analysis, error group, subclass and failure, Snorre B D-3 H

Error Subclass	Explanatory	Error Group	Collceted	Failure
Solids Settling	44 %	Acc. Solids	44 %	Hole Cleaning
Dogleg	56 %	Crooked Wellbore	56 %	Operation

The symptoms, symbolic concepts and potential resulting errors are presented graphically in figure 4.9.

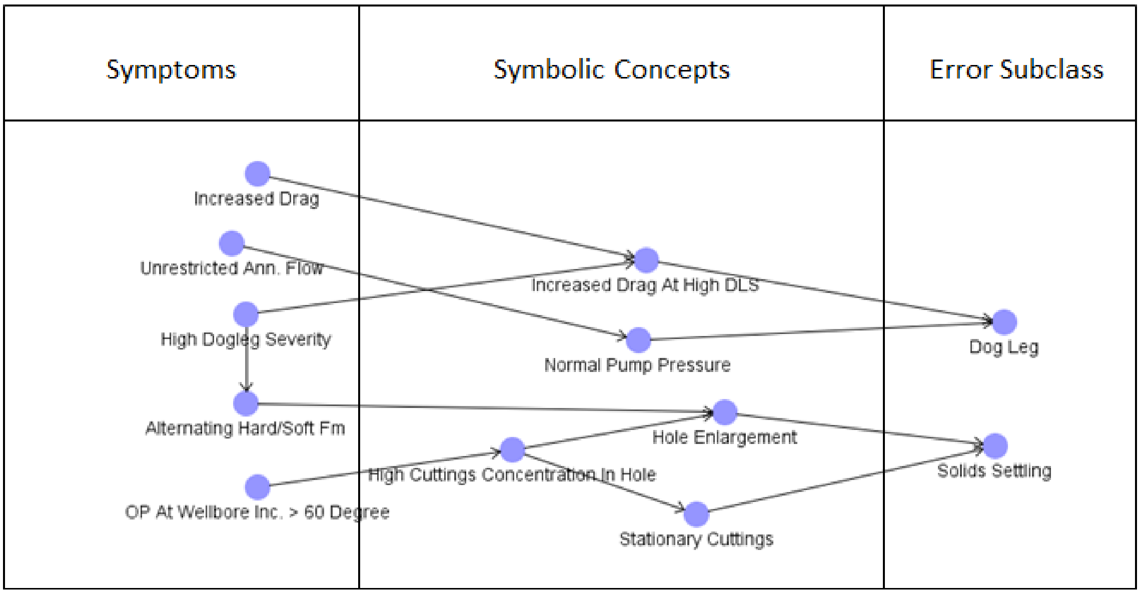

Figure 4.9: Results of the field analysis, case 18, Snorre B D-3 H, case one

Snorre B D-3 H: Running 14" casing

The second event that was studied on Snorre B D-3 H included the cases 19 – 21. The symptoms of the cases have been collected and analysed together. The results can be seen in table 4.11. The same method of analysing and displaying the results as for the three events above has been used.

TABLE 4.11: Case 19 – 21, symptoms, path strength and explanatory strength resulting in the main cause cuttings accumulating

Case	**Symptom**	**Strength**	**Path Strength**	**Main Cause**	**Expl. Strength**
	Wellbore Inc. > 60 ^{o}	0,5 · 0,7	0,35	1 b.	0,30
	Wellbore Inc. > 60 ^{o}	0,5 · 0,7	0,35	1 a.	0,39
	Cav./Cutt. Plowing	0,7	0,7	1 a.	
	Took Weight	0,7 · 0,7	0,49	1 a.	
	Took Weight	0,7 · 0,7	0,49	4 a.	0,11
19, 20	High DLS	0,7	0,7	4 a.	
21	Cuttings Storage Tanks Unavailable	0,9 · 0,9 · 0,7	0,57	1 a.	
	Alt. Soft/Hard Fm.	0,5 · 0,9	0,45	2 a.	0,20
	Alt. Soft/Hard Fm.	0,5 · 0,7	0,45	1 b.	
	Excessive Cutt./Cav.	0,7 · 0,7	0,49	2 a.	
	Excessive Cutt./Cav.	0,7 · 0,9	0,63	1 b.	
	Excessive Cutt./Cav.	0,5 · 0,9	0,45	1 a.	
	Sum		4,72		1.0

From table 4.11 it can be seen that the main cause of the second restriction event on Snorre B D-3 is accumulating cuttings with explanatory strength 39 %, and the secondary cause is cuttings accumulating in washout, with explanatory strength of 30 %. Both the main cause and the secondary cause results in the error subclass Solids Settling. Their explanatory strength are therefore added, resulting in the strength 69 %. Table 4.12 presents the explanatory strengths of the error subclasses, error groups and the failure resulting from the restriction event. Both restriction causes are subclasses of Solids Settling, which again are the error subclass of Accumulated Solids. The main error Accumulated Solids, resulted then in explanatory strength of 69 %. The resulting failure is Hole Cleaning Operation. Reactive Fm. proved to be the secondary error with explanatory strength of 20 %.

The symptoms, symbolic concepts and potential resulting errors are presented graphically in figure 4.10.

Collected Analysis

When the error and failure groups are collected and related to each other, the error group Reactive Fm. proved to be the most frequent cause of restriction

Table 4.12: Case 19 – 21, results field analysis, error group, subclass and failure, Snorre B D-3 H, case two

Error Subclass	**Expl.**	**Error Group**	**Collceted**	**Failure**
Solids Settling	69 %	Acc. Solids	69 %	Hole Cleaning
Enlarged Wellbore	20 %	Reactive Fm.	20 %	Operation
Dogleg	10 %	Crooked Wellbore	10 %	

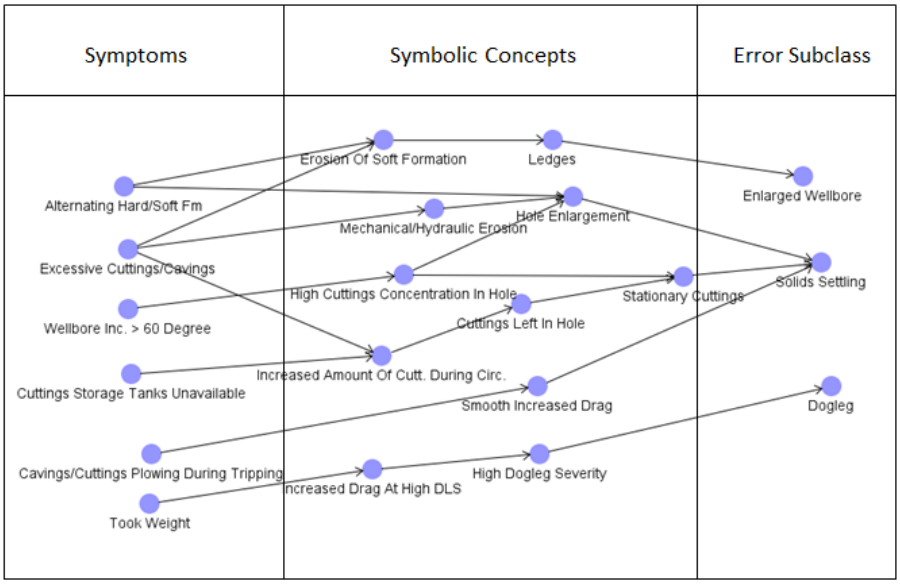

Figure 4.10: Results of the field analysis, case 19 – 21, Snorre B D-3 H, case two

with explanatory strength of 48 %. The error subclass, Enlarged Wellbore, proved to be the most likely cause of restrictions, with explanatory strength of 47 %. Accumulating Solids was the second most frequent cause of the restriction with explanatory strength 37 % and error subclass Solids Settling (29 %). The results are shown in table 4.13 and 4.14.

Table 4.13: Results field analysis, collected error groups

Error Group	**Expl. Strength**	**Percentage**
Accumulating Solids	0,37	37 %
Crooked Wellbore	0,12	12 %
Reactive Formation	0,48	48 %
Equipment Failure	0,03	3 %
Sum	1,0	

Error Subclass	**Explanatory Strength**	**Percentage**
Solids Settling	0,29	29 %
Enlarged Wellbore	0,47	47%
Dogleg	0,09	9%
Increasing Filtercake	0,12	12 %
Drill String Failure	0,03	3 %
Sum	1,0	

Table 4.14: Results field analysis, collected error subclasses

5. Evaluation of Results

The scope of this thesis was to reveal the cause of HKL restrictions by the means of the Knowledge Model. The evaluation will start by discussing the results of the 21 restriction cases found from the RTDD and the discovered consistencies between the HKL signatures and the restriction cause. The results of the different restriction events will first be discussed separately, before they are discussed in relation to each other.

Suggested improvements on how to minimize NPT next time a similar restriction event occurs, will be presented. The cause of the restriction events given by data from Statoil was found by means of the Knowledge Model. The advantages and limitations of the model and the data applied to determine the restriction cause will be discussed in the next chapter. The following discussion is based on the information presented in chapter 1 to 4, and is the investigators own interpretations.

Main Symptoms of Each Restriction Cause

The symptoms that result from a restriction event may be seen at the surface, before and during the restriction event. As a symptom may result from one or more of the restriction causes, it may be hard to determine the restriction cause. However, if one symptom is put in context with several other symptoms and parameter during the drilling operation, the main restriction cause can be determined.

By means of the Knowledge Model, the symptoms were related to error subclasses and the main restriction causes by different degree of probability. The five symptoms that most strongly indicated each restriction proved diverse and can therefore be separated from each other and used to reveal the cause of the restriction during the drilling operation. The symptoms and their related restriction cause, can be seen in table 5.1.

TABLE 5.1: Main symptoms, in general, of the four investigated HKL restrictions

Symptom	**Path Strength**	**Failure**	**Main Cause**
Low Flow Rate	0,81		
Wellbore Inc. > 60 Degree	0,81	Hole Cleaning	
Less Cuttings On Shaker	0,73	Operation	1 a.
Cavings/Cuttings Plowing	0,7		
Low RPM	0,7		
Excessive Cuttings And Cavings	0,9		
Long Periods Of Circulation	0,81	Hole Cleaning	
Cavings/Cuttings Plowing	0,7	Operation	1 b.
Difficult Re-Entry Cond.	0,63		
Enlarged Caliper	0,5		
Periods Of Still Stand	0,9		
Overpull After Flow Check	0,81	Hole Cleaning	
Restricted Rotation	0,81	Operation	1 c.
Unrestricted Ann. Flow	0,7		
Very High Overpull	0,56		
Difficult Re-Entry Cond.	0,9		
Hard Stringers	0,9	Hole Cleaning	
Enlarged Caliper	0,9	Operation	2 a.
Pack Off	0,81		
Excessive Cuttings/Cavings	0,81		
Excessive Cuttings/Cavings	0,9		
Enlarged Caliper	0,9		
Excessive Wellbore Stress	0,81	Stuck	2 b.
Pack Off	0,81	Pipe	
Non-PDC Cuttings	0,81		
Gumbo Shale Produced	0,9		
Formation Fluids/Mud Interaction	0,9	Stuck	
Shallow Depth	0,81	Pipe	3
Long Open Hole Time	0,81		
Bit Balling	0,81		
High DLS	0,81		
Increased Drag	0,7	Stuck	
Unrestricted Ann. Flow	0,63	Pipe	4 a.
Tight Spot	0,5		
Took Weight	0,49		
High WOB	0,63		
Hard Stringers	0,57	Equipment	
Very High Torque	0,5	Failure	4 b.
Very High Drag	0,45		
High Annular Velocity	0,5		
Low MW	0,9		
Gain In Mud Pit With Pumps Off	0,9		
High Swab Pressure	0,63	Blowout	4 c.
Increased SPP	0,63		
Altered Mud Properties	0,63		

If all the five symptoms that are mentioned for each restriction group are fulfilled, the probability is high for making the right diagnosis. If the symptoms are also put in context with the HKL signature that can be seen on the surface, the chances of making the correct preventing actions are even higher.

21 Cases of Restrictions

Out of the daily drilling reports, RTDD and other available data provided by Statoil, five events where several restriction cases occurred, were selected. Out of the five events, 21 cases of restrictions were found. Detection of the 21 cases gave the opportunity to discover additional relationships between symptoms and restrictions.

When the symptoms and relationships from the 21 cases was collected, only information about what happened before and during the restriction can be used. As the cause of the restrictions are determined, all available information have been utilized. Such information includes knowledge about what occurred after the restriction, contact with experts and MWD data. When this is included in the analysis, a comprehensive and thorough solution is the result. Examples of when additional information are applied are when cavings are seen over the shakers a short time after overpull has been experienced, when HKL signature investigator Bjerke (2013) has been contacted to assist in verifying the investigated HKL signature assumptions and when MWD gives information about the dogleg severity. In that way, the analysis has provided a solution to the restriction cases.

The symptoms and their relationships with the highest path strength, and thus the strongest contribution when the explanatory strength was calculated, are listed in table 5.2.

All symptoms with the strongest path strength result from the detected main cause, except for the symptom at case no. 18. The Knowledge Model detected the main cause to be local dogleg, and not cuttings accumulation, as the symptom is resulting from.

14 of the 21 selected cases indicated different mechanical wellbore instability errors as the main cause of the HKL restriction. Six cases indicated cuttings accumulating in the wellbore to be the main cause, while one case indicated local dogleg. This can be seen in table 5.3.

TABLE 5.2: Cases and their main error

Case	Symptom	Path Strength	Main Cause
2	OP After Flow Check	0,9	1 c.
3	TW At High Wellb. Inc.	0,81	1 a.
4	Hard Stringers	0,7	2 a.
7	Pack Off After Rot./Circ.	0,81	2 a.
12	Excessive Cutt./Cav.	0,9	2 b.
13	Fm. Fluid/Mud Interact.	0,9	2 b.
16	OP At Depth Of BHA Comp.	0,9	2 a.
18	Wellbore Inc. > 60 ^{o}	0,81	1 a.
20	Cav./Cutt. Plowing	0,7	1 b.

TABLE 5.3: Cases and their main error

No. of Cases	Main Cause	Error	Error Subclass
14	Mechanically Unstable Wellb.	Reactive Fm.	Enl. Wellbore
4	Cuttings Accumulating	Acc. Solids	Solids Settling
2	Cuttings Accumulating	Acc. Solids	Inc. Filtercake
1	Local Dogleg	Crooked Wellb.	Dogleg

The 14 cases that indicated Reactive Formation were all caused by erosion of the wellbore wall. Figure 5.1 presents a part of the technical errors that may occur during the drilling operation. The figure has included the errors that are relevant for the analysis of these results. As can be seen from the figure, Reactive Fm has subclasses Enlarged Wellbore, Dissolving Limestone and Reactive Shale. Reactive Fm. leading to Dissolving Limestone or Reactive Shale is mainly a chemical process, while Enlarged Wellbore can be interpreted as a combination of both a chemical and a mechanical process.

The wellbore wall will be affected by both hydraulic and mechanic erosion, which sometimes result in wellbore enlargement. As mentioned in Chapter 3.2, Azar (2006) separated between three different reasons for why a wellbore is unstable. The two first reasons was then in-situ stress and erosion by circulation or BHA stress, which was decide to be included as mechanically unstable wellbore. Drilling through shale formation causes 70 % of all wellbore instability problems (Osisanya 2011). Silty claystone could be seen at surface during circulation and rotation of both Gudrun A-12 T2 and Gudrun A-5, which is a sign of erosion of the weak clay formation. Combined with erosion by the BHA, the wellbore has been both mechanically and hydraulically eroded.

In addition, Enlarged Wellbore is a subclass of Collapsing Hole (figure 5.1, which again is a subclass of the error Compressively Stressed Wall. Compressively Stressed Wall is a mechanical error, which makes the assumption of Enlarged Wellbore being a combination of both mechanically and chemically unstable formations, stronger. For that reason, the investigator has concluded with Reactive Fm. as the main error for mechanically unstable wellbore.

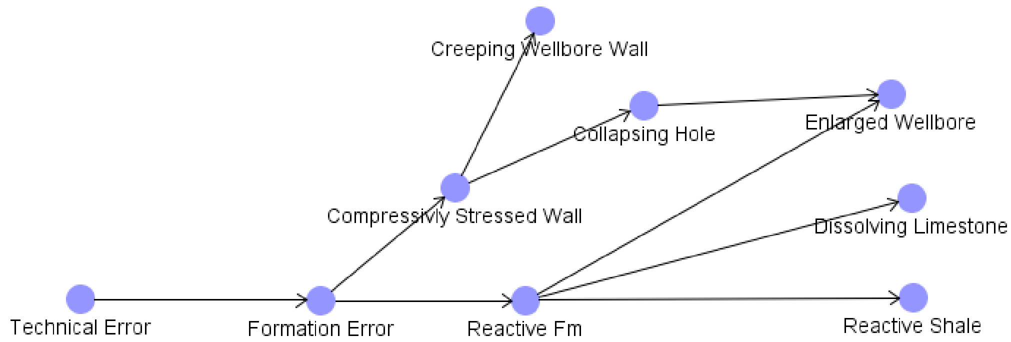

Figure 5.1: Symptoms, error and failure resulting from differential sticking

Six cases indicated different causes of Accumulated Solids. Four cases resulted from the error subclass Solids Settling, where both cuttings accumulating in the well and in washouts are embedded. To determine whether cuttings accumulating in washouts or in the wellbore are the restriction cause, are challenging. Case 21 proved that cuttings accumulating in washouts were the main cause, with explanatory strength of 44 %. However, in the same case, cuttings accumulating in the wellbore resulted in explanatory strength of 41 %. One of the symptoms seen at the surface was that large amounts of cuttings were produced at one point, which may strengthen the result found from the analysis.

HKL Signatures

A short study of HKL signatures have been done in this thesis. The signatures that appeared at surface when a restriction case was found have been compared in order to find similarities and differences. The study showed that the HKL signature that can be seen at the surface when the HKL restriction is due to cuttings accumulation can be separated from the other HKL signatures. Bjerke (2013) divided into fixed and moveable HKL signatures, where the signal of the overpull of fixed signatures is controlled by the pipe stretching and the moveable has a smoother build-up of the overpull signal.

The HKL signature of differential sticking has already been determined by Cordoso et al. (1995). The characteristics of the HKL signature of differential sticking could be recognized from case 2.

The HKL signature of mechanically unstable wellbore proved to be a sudden increase in HKL when the pipe stretch is completed, where the spot of overpull is fixed. The HKL signature of cuttings plowing is slowly increase during tripping until enough cuttings have been plowed along with the pipe and maximum overpull is reached. As the cuttings are plowd along with the BHA are the spot of overpull moved upwards in the well. A comparison can be seen in figure 5.2.

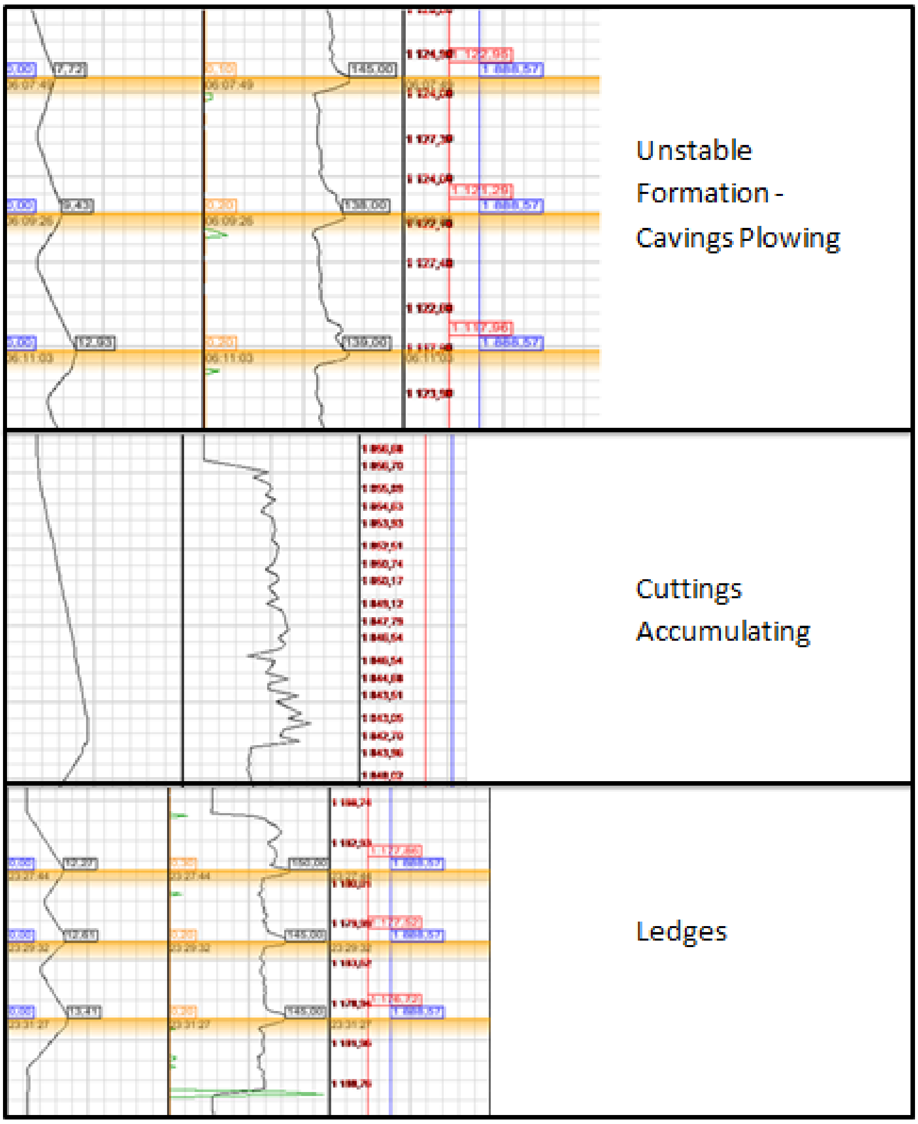

FIGURE 5.2: Comparison of the HKL signature of ledges, cuttings accumulating and unstable formation

The comparison proved that it is possible to separate the HKL signatures of mechanically unstable wellbore from accumulating cuttings. However, the signature of local dogleg is similar to the signature of ledges, and may be hard to separate from each other. Both signatures are characterized by a sharp overpull signal at a fixed spot (Bjerke 2013), as seen in figure 5.3.

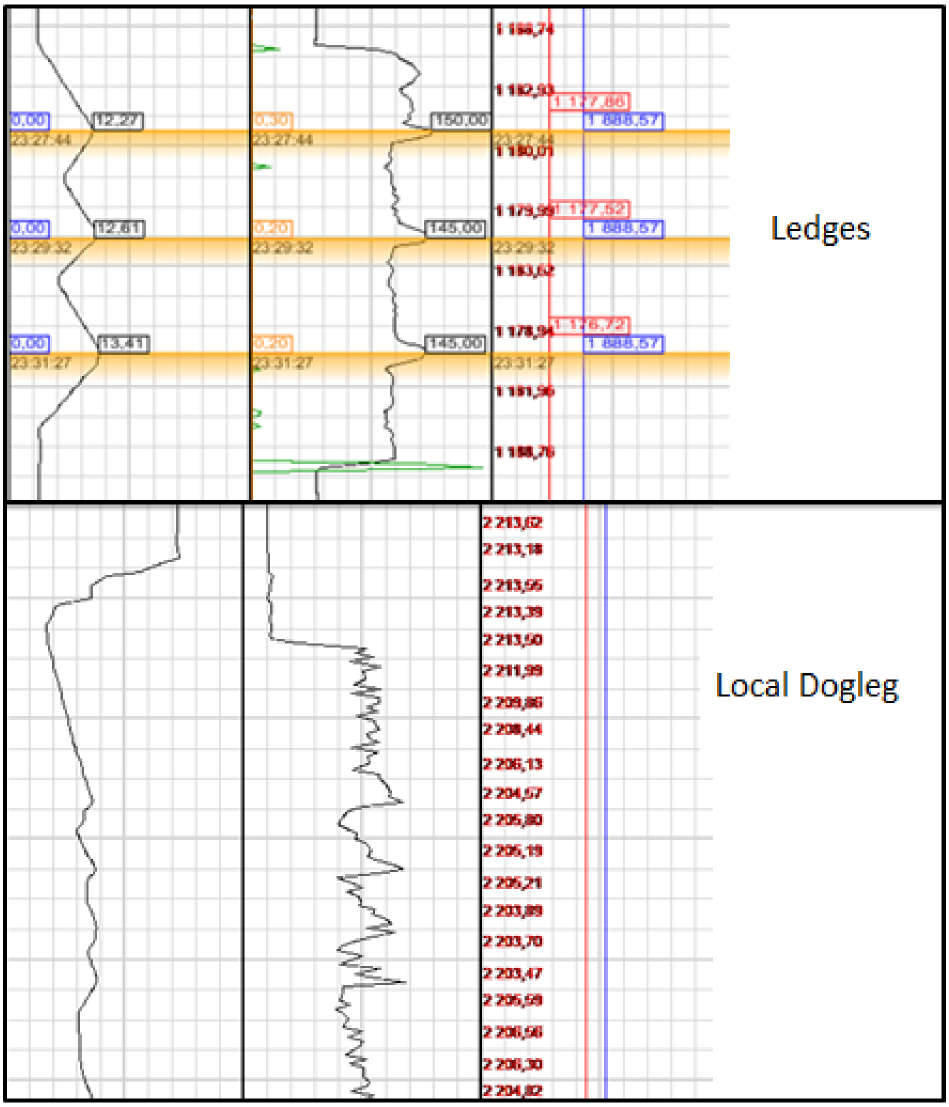

Figure 5.3: Comparison of the HKL signature of ledges, cuttings accumulating and unstable formation

To separate these restrictions from each other, the HKL signal have to be put in context with symptoms that can be observed at the surface and other data available from the drilling process. A tight spot due to high DLS may also have been noticed during the drilling operation. The Knowledge Model managed to separate HKL restrictions caused by local dogleg and cuttings from each other.

Field Analysis

Gudrun A-12: Drill string parting during tripping after drilling the 17,5" section

The analysis proved the main cause of the restriction on Gudrun A-12 to be differential sticking which resulted in the failure Drill String Twist Off. The symptoms resulted in the error subclass Increasing Filtercake, with calculated explanatory strength of 49 %. Increasing Filtercake is the subclass of the error group Accumulating Solids, which resulted in explanatory strength of 80 %. The secondary error is Reactive Fm. and Crooked Wellbore, both with explanatory strength of 10 %.

As mentioned in Chapter 3.2, differential sticking occur when the drill string has been stationary for some time over a permeable formation in a well with overbalanced pressure. Severe overpull was observed straight after flow check, and 90 ton overpull was pulled before the drill string was free. The HKL was then 15-20 ton less than normal, and when the drill string arrived at surface, it was found that parts of the drill string was left in the hole.

Differential sticking is one of the major concerns when drilling overbalanced (Azar 2006), and should therefore always be an issue after flow check. 90 ton overpull was observed straight after flow check, in addition, symptoms of differential sticking had recently been observed at the same area. If the drilling crew had been more aware of the symptoms of differential sticking, preventive actions could have been initiated when overpull was observed and the failure and increased NPT may have been avoided.

Gudrun A-12 T2: Sevral spots of overpull during trpping after driling the 17,5" section

The main cause of the restrictions on Gudrun A-12 T2 proved to be ledges which resulted in the failure Hole Cleaning Operation. The symptoms pointed out Enlarged Wellbore (74 %) to be the error subclass which led to the restriction, with error group Reactive Formation. The second most likely cause of the restriction proved to be Accumulating Cuttings with explanatory strength 17 %.

As mentioned in Chapter 3.2, ledges may be created when alternating soft/hard formations are drilled. Ledges will cause the BHA to hang up at the edge of the hard formation, causing increased HKL. Four of the components of the BHA had the same outer diameter (OD) as the wellbore diameter (17,5”). The components and their distance from the bit can be seen in table 5.4.

Table 5.4: The BHA components with OD 17,5”, Gudrun A-12 T2

BHA Component	**Distance from bit**
Stabilizer sleeve	1 m
In line stabilizer	16 m
Stringer stabilizer	28 m
Roller reamer	34 m

An overview of the depth of the hard stringers and to which 17,5” BHA component they may have been hanged up to, are listed table 5.5. By subtracting the overpull (OP) depth from the depth of the hard stringer, the components which were restricted at the stringers can be determined (Bjerke 2013).

Table 5.5: Depth of the BHA components with OD 17,5” compared to the depth of the hard stringers, Gudrun A-12 T2

Stringer Depth (MD)	**OP Depth (MD)**	**BHA Component**	**OP Depth – Stringer Depth (MD)**
3019 - 3021	3050	Roller Reamer	31
3041 - 3042	3070	Stringer Stabilizer	29
3069 - 3070	3084	In line Stabilizer	15
3112 - 3113	3144	Roller Reamer	32
3126 - 3128	3144	In line Stabilizer	18
3126 - 3128	3157	Roller Reamer	31
3171 - 3173	3191	In line Stabilizer	18

When alternating soft and hard formations are drilled, increased attention should be paid on optimizing WOB, BHA components and drilling fluid parameters to prevent erosion of the soft formation and thus the creation of ledges. Drilling through such formations causes increased challenges when selecting the sufficient bit to perform when drilling hard stringers and soft formations. PDC bits are favoured for soft formations, while roller cone bits are favored for the hard stringers (Thomson 2011). The bit used for the interval with hard stringers was drilled was a Kymera bit with 3 blades and PDC cutters and 3 roller cones. The bit was therefore suited for the heterogeneous environment and should not have caused the failure. A BHA with components of smaller OD could have been chosen, however, the drilling performance would then have been worsened.

Low rotation caused severe stick-slip and high lateral vibrations, optimal drilling parameters were found at low ROP and high RPM and WOB. The soft formation may have been eroded due to the long periods spent on drilling the sections. Back-reaming through areas where ledges may potentially develop could have prevented the development of ledges and minimizing the time spent washing and working through the overpull areas. However, the overpull areas were carefully watched and passed without causing further damage to the section.

Gudrun A-5: Cavings production and overpull during drilling of the 17,5" section

The restriction that occurred during tripping out of the well after the 17,5" section was drilled to 1881 m, was found to be mechanical unstable wellbore with failure Collapsing Hole. The resulting error was Reactive Formation with explanatory strength of 93 % and error subclass, Enlarged Wellbore with explanatory strength of 74 %. The secondary error was found to be the Accumulating Solids, with explanatory strength 7 %.

Overpull was first observed at an area with two hard stringers. Two of the components of the BHA has OD same as the wellbore diameter (17,5"). The components and their distance from the bit can be seen in table 5.6.

Table 5.6: The BHA components with OD 17,5", Gudrun A-5

BHA Component	Distance from bit
In line stabilizer	18,5 m
Roller reamer	31,5 m

To find out if the overpull was caused by the BHA components being restricted by the hard stringers, the overpull depth was subtracted from the stringer depth. If the result is the same as the depth at which the BHA component are located, the overpull is caused by the ledges. Table 5.7 presents the depths.

Table 5.7: Depth of the BHA components with OD 17,5" compared to the depth of the hard stringers, Gudrun A-5

Stringer Depth (MD)	OP Depth (MD)	BHA Component	OP Depth – Stringer Depth (MD)
1161	1178	Stabilizer	17
	1191	Roller reamer	30
1178	1197	Stabilizer	19
	1207	Roller reamer	29

To pass the restrictions, the well was circulated and pipe reciprocated. This led to large amount of mechanical cavings and cuttings to be produced. The cavings were splintery and blocky, which as seen in table 3.4, are produced either during UBD or in fractured formations. The well is neither. The cavings and cuttings have most likely been generated by the BHA as it hits the instable and brittle formation.

The well was circulated a total of 16,8 times BU before the string could be pulled to surface without overpull. This was separated in three different periods, as overpull was seen after the two first periods. When the string could be pulled without overpull, it was backreamed through the problems areas. This had not been done in the two first attempts of pulling to surface and may have decreased the time spent on the trouble areas.

No preventative measures were taken when it was discovered that formation fluids had been sucked into the drilling mud. However, some amount of water will always be extracted from the formation fluid and into the mud, but there is no information about the amount of water exchange. Large amounts of water exchange would have weakened the formation and caused it to become brittle and easily eroded during rotation and circulation. The sections of overpull occurred in the area where the formation water was extracted.

Snorre B D-3 H: Tight spot at 2200 m

Two events where investigated at Snorre B D-3 H. The first event, the tight spot at 2200 m, proved to be due to Local Dogleg with resulting failure; Hole Cleaning Operation. The symptoms and symbolic concepts led to Dogleg to be the error subclass with explanatory strength of 56 %, belonging to the error group Crooked Wellbore. The secondary error was Accumulated Solids, with explanatory strength of 44 %.

The tight spot was located at a depth with high dogleg severity (DLS) (4,5 degree/30 m) at wellbore inclination of 65 degree. The interval from 2123m to 2179 m was reamed due to high DLS and the presence of a hard stringer. The combination of high DLS and stationary cuttings present when wellbore inclination is more than 60 degree, will most likely have caused overpull when the drill pipe pulled out.

The tight spot occurred at 2200 m, which is right below the interval that was reamed. The DLS was still high at this point (4,1 degree/30 m), and it would have been beneficial to continue the reaming throughout the section of high dogleg.

Snorre B D-3 H: Running 14" casing

The second event that was interpreted was the restriction during running of casing. The analysis proved the restriction to be caused by cuttings accumulating with the resulting failure Hole Cleaning Operation. The symptoms and symbolic concepts pointed to Solids Settling as the error subclass of highest probability to cause the restriction (69 %), with Accumulating Solids as the main error group. The secondary error proved to be Reactive Formation with explanatory strength of 20 %.

Increased amount of cuttings (PDC and non-PDC) were produced when the interval from 1994 – 1966 m was circulated clean. Due to logistic problems regarding the cutting storage capacity, it was decided to stop circulating and POOH. This might have caused some of the cuttings to be left in the hole. As seen in Chapter 3.2, cuttings will start to accumulate in the well at wellbore inclination more than 30 degree (refer to figure 3.2). The casing got stuck at 1804 m. At this depth, the wellbore inclination was 45 degree, which is at an inclination where cuttings will accumulate. The casing was worked down to 2050 m where it was stuck. The wellbore inclination was here 51 degree, an angle at which the cuttings are more or less stationary.

The casing was free after pulling to 355 ton, which is 45 ton above the max limit of the BX-elevator. 59 hours were spent from the casing reached the first tight spot at 1804 m until it was free and could be pulled to the surface. If the well had been circulated clean before the casing was run, NPT may have been prevented and the casing may have reached TD as planned. For this case, it may have been beneficial to wait for the cuttings storage tanks to be emptied so the well could have been circulated clean.

All events collected

When combining the results, and looking at the collected analysis, two error groups stand out as the most frequent cause of HKL restrictions. The error group, Reactive Formation, proved to be the most frequent cause of restriction with explanatory strength of 48 %, followed by Accumulating Cuttings with strength 37%. When breaking down into error subclasses, Enlarged Wellbore has the explanatory strength of 47 % while Solids Settling has 29 %. Table 5.8 show the most probable failure cause of each event in addition to the primary and secondary error.

Table 5.8: Results collected analysis, failure, error and subclasses of each restriction event

Wellbore	**Failure**	**Primary Error**	**Secondary Error**
Gudrun A-12	Drill String Twist Off	Accumulating Solids – 80 %	Reactive Formation –10 %
Gudrun A-12 T2	Hole Cleaning Operation	Reactive Formation – 74 %	Accumulated Solids – 17 %
Gudrun A-5	Collapsing Hole	Reactive Formation – 93 %	Accumulating Solids – 7%
Snorre B D-3 H	Hole Cleaning Operation	Crooked Wellbore – 56 %	Reactive Formation – 44 %
Snorre B D-3 H	Hole Cleaning Operation	Accumulating Solids – 69 %	Reactive Formation – 20 %

6. Self Assessment

Quality and Shortcomings of Model

The results of the analysis is a numerical value that indicates the most frequent cause of restrictions out of five different cases. The value gives the reader an indication of which errors to look for when drilling wells in the future. As for most engineers, numbers are preferred results. The fact that the result of an analysis performed by the Knowledge Model is a numerical value, gives engineers a better understanding of the result and increased chances that the restrictions may be recognized at an earlier stage next time the symptoms appear.

The investigator determines each relation based on their own opinion. The relationship between the symbolic concepts are thus the relationship that the investigator deems best fit, which may vary from person to person. The result of an investigation done by the Knowledge Model might thus be different depending on who is performing the analysis. This can both be an advantage and a disadvantage of the model; if a group of people are set to do the same analysis separately, the results may be compared and the conclusion become even stronger.

The Knowledge Model used for this analysis was a simplified version. The simplification comprised a decreased amount of relationships to be included in the analysis as well as only one level of subclasses. The results may be more uncertain and less comprehensive than if the complete model had been applied. The simplifications were made as a result of the investigators lack of experience with the model.

When the restriction cases were analysed by means of the Knowledge Model, information about what happened after the cases was included. A comprehensive solution was created when additional information, such as symptoms seen after the restriction event, contact with experts and MWD, were included in the analysis.

The additional information made the solutions extensive and the restriction cases was solved.

The model is still under development. As mentioned in chapter 2.1, Skalle et.al (2013) recently started developing the model regarding real-time drilling data analysis. As the Knowledge Model is under constant development gives the investigator the opportunity to analyse and treat the data without depending on strict rules and regulations. The table of symptoms in Appendix B is an example of this. The work done in the table is close to the final product of knowledge modelling, but some work are still left before it is complete.

Quality of the Information Applied

The information applied for the analysis was RTDD and drilling reports obtained from Statoil. The RTDD and drilling reports from seven wells drilled by Statoil was available, in addition to the directional data of each well. The data included some assumptions regarding the cause of the HKL restrictions, however, with insufficient descriptions. This gave the investigator the opportunity to use the information required for the model as input, analyse the restrictions and determine the cause of the restriction without knowing the conclusion in advance.

The data applied for the analysis was based on drilling reports and RTDD. The quality and the information included in the drilling reports varied from comprehensive to lacking of important information, making the analysis challenging.

Of the seven wells available, four wells were drilled on the Gudrun field, three wells drilled on the Snorre field and one at Gullfaks field. The fact that Snorre B is a semi-submersible drilling rig, Gudrun is a jack-up and Gullfaks a fixed rig, makes the comparison of the HKL-signature challenging. It would have been beneficial to choose wells that were all drilled by the same type of drilling rig.

Further Work

The analysis should be performed using the Knowledge Model in its full extent. The analysis would then have become more comprehensive. In addition, only one level of subclasses was used for this study. Adding deeper levels of subclasses would lead to additional relationships which make the study more inclusive.

Additional information, such as pressure data and lithology data, would have led to the discovery of new symptoms and deeper relationships. The complete description of the restriction event done by the operator, would have caused the solution to be known in advance of the analysis, but would have included comprehensive information obtained from the investigation performed by the company.

The work of creating a complete table of symptoms, where the method of knowledge modelling is utilized in its full extent, should be continued. A complete table would make the determination of main restriction causes through knowledge modelling more reliable. Numerous restriction events should be analysed to discover increased number of symptoms and new relationships to include in the table. As new symptoms and relationships are added to the model, it becomes more comprehensive and the goal of determining the cause of a restriction based on the symptoms seen at the surface, comes closer.

7. Conclusions

Analysis and Result

- 21 cases of restriction were found from drilling reports and RTDD. Out of the 21 cases, 14 was caused by Reactive Formation, six by Accumulating Solids and one from Crooked Wellbore.
- Field analysis of the five selected restriction events, proved Reactive Formation to be the most frequent error with explanatory strength of 48 %. The second most frequent error was Accumulated Solids, with explanatory strength of 37 %. The error subclass that most frequently caused restriction was Enlarged Wellbore, with explanatory strength 48 %.
- Comparison of the HKL signatures showed that the HKL signature of accumulating cuttings can be separated from the HKL signature of mechanically unstable wellbore. If the symptoms are put in context with the HKL signature the probability of making the correct diagnosis of the downhole problem increases.

The Model

- A simplified version of the Knowledge Model have been used to analyse five restriction events and 21 cases of restrictions. Symptoms have been interpreted from drilling reports and RTDD, and used as input for the model. The final result gave a numerical value of different probability describing which error that most likely caused the restriction event.
- The model are relaying on one persons opinion and experience. If a group of persons had analysed the same events and compared results, the conclusion mights have been stronger.

- The model successfully determined the restriction causes and created a solution.

The Information

- The data applied for the analysis was based on drilling reports and RTDD obtained from Statoil. The quality of the drilling reports and the information included, varied from being comprehensive and thorough to lacking important information.
- The data included some assumptions and descriptions about the restriction events, but with insufficient descriptions. This gave the investigator the opportunity to analysis the restrictions without knowing the solution in advance.

Further Work

- A simplified version of the Knowledge Model was used for this analysis. Using the model in its full extent would have been beneficial.
- Continued development of the model by analysing numerous restriction cases would discover additional relationships and lead to a more comprehensive model. Additional data would have led to the discovery of new symptoms and deeper relationships.

8. Nomenclature

Abbreviations

BHA	**B**ottom **H**ole **A**ssembly
CEC	**C**ation **E**xchange **C**apacity
DLS	**D**ogleg **S**everity
ECD	**E**quivalent **C**irculation **D**ensity
EFD	**F**racture **C**irculation **D**ensity
HKL	**H**ook **L**oad
KM	**K**nowledge **M**odel
LC	**L**ost **C**irculation
MD	**M**easured **D**epth
NPT	**N**on – **P**roductive **T**ime
OBM	**O**il **B**ased **M**ud
POOH	**P**ull **O**ut **O**f **H**ole
RIH	**R**un **I**n **H**ole
RTDD	**R**eal – **T**ime **D**rilling **D**ata
SPP	**S**tand **P**ipe **P**ressure
UBD	**U**nder **B**alanced **D**rilling
WBM	**W**ater **B**ased **M**ud
WOB	**W**eight **O**n **B**it

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A. Appendix A

A summary of the five different events are presented below.

Case 1 – 3, Drill string parting during tripping after drilling the 17,5" section, Gudrun A-12

A limestone stringer from 3100 to 3102 m was hit during drilling of the 17,5" section. ROP decreased and could not be optimized again so it was decided to POOH. Before POOH, the well was flow checked for 15 min. 90 ton overpull was observed straight after flow check. During pulling of the first three stands, the weight was fluctuating between 180 and 215 ton before the weight increased to 230 ton when the forth stand was pulled. The weight stabilized at 165 ton, which is 15 ton lower than the normal up weight. The drill string was pulled to surface without further problems, but with 20 tons lower weight than during last trip. When the BHA arrived at surface, it was found that 90 m was left in the hole.

Case 4 – 11, Overpull during trpping after driling the 17,5" section, Gudrun A-12 T2

The well was drilled to 2818 m when the Geopilot stopped working. Installed new Geopilot and RIH with stabiliser 2" undergauged. 20 ton weight was taken at 2750 m, which is in area of several hard stringers. Had to ream to get further down and string torqued up several times. Optimal ROP was found at 1,4 – 4 m/hr with high RPM and high WOB. TD was set at 3244 m due to no further progress and after drilling very many hard stringers. The well was circulated before POOH.

During POOH from 3244 m to 3050 m, overpull was experienced several times in areas where hard stringers are present. Overpull of 15 ton was observed at 3191 m, 3157 m and 3144 m. The restrictions were passed by RIH below them and work the string through. A tight spot at 3132 m required connection of TDS and to lubricate the string through the area. At 3124 m, 15 ton overpull was observed and could not be passed. The drill pipe was washed/reamed back to TD at 3244 m before the well was circulated while the pipe was reciprocating. The pipe could then be pulled to 3098 m without observing any restrictions, before several areas of overpull again was observed between 3084 m and 3070 m. Max overpull in the interval was 30 ton. A tight spot at 3097 m was passed by washing while rotating the pipe. A stringer at 3050 m caused 35 ton overpull and the string stalled out with 40 kNm. The string was freed by jarring down. Additional tight spots were seen from 3070 - 2400 m.

The well was circulated and cleaned while POOH from 2273 - 2100 m. During the cleaning, large amounts of cuttings were seen over the shakers and increased ECD and drag was observed. The parameters were adjusted to reduce ECD and avoid pack off. POOH to surface without further problems.

Case 12 – 17, Cavings production and overpull during tripping, Gudrun A-5

The 17,5 section was drilled to 1888. ROP had to be kept at 20 m/hr to adapt the drilling progress to the weather and the cuttings offloading to the boat. Only 2 HCB tanks left for cuttings return and cuttings offloading was not possible due to the weather conditions. Drilling was stopped and well circulate clean. The inclination of the well allowed circulation with low RPM to avoid both damage to the wellbore and wear on the downhole tools. In addition, high temperature in the SCR room required reduced flow.

During POOH, 15 ton overpull was observed at 1290 m in addition to several tight spots in the interval from 1217 m to 1207 m, all in areas where hard stringers had been drilled. Max overpull occurred at 1207 m. RIH to 1350 m, circulated 5 times BU while rotating and reciprocating stand. Large amounts of cuttings could be seen over the shaker in the beginning of the circulation. 5 ton overpull was seen at 1204 m and 15 ton overpull was at 1197 m when POOH. RIH to 1206 m and 15 ton overpull was experienced at 1191 m and 25 ton at 1177,5 m. RIH to 1184 m and observed 25 ton overpull at 1176 m when POOH. RIH to 1247 m, circulation broken and string rotated while reciprocating stand. Circulated 7,5 x BU. Large amounts of cuttings ranging in size from 1 cm to 4-5cm could be seen over shaker in the beginning, including an increasing amount of mechanical cavings (flat and thin).Thus, the cuttings where both cuttings produced by the PDC bit and non-PDC produced cuttings. This indicated that the cavings was produced as the drill string was rotated.

POOH after cleaning the well and 25 ton overpull was experienced at 1125 m. RIH to 1139 m and got 25 ton overpull at 1135 m, 1123 m, 1121 m and 1117 m. RIH to 1215 m and circulated hole clean before backreaming from 1215 m to 1012 m, and POOH to surface.

Case 18, Tight Spot at 2200 m, Snorre B D-3

During drilling of the 17,5" section to TD at 2626 m, several interval had to be reamed due to high dogleg and hard stringers. The interval from 2123 – 2179 m had to be reamed due to high dogleg and hard stringers in area. Had to work through tight spot from 1850 –1835 m, and RIH to 1994 m. Pulled to 1966 m where the well was cleaned by circulating and rotating pipe. As more cuttings was produced when the well was circulated, it was decided to stop circulating and POOH due to logistics problems regarding cuttings storage capacity. Overpull of 30 ton was experienced straight after circulation was stopped.

Case 19 – 21, Running 14" casing, Snorre B D-3H

RIH with 14 casing, had to work casing from 1753 m to 1769 m and got backflow up casing occurred again at 1804 m. Attempted to break circulation and to work string from 1804 m to 1785 m, but it was nogo. String took 90 ton weight at 1804 m and well packed off several times. Circulation could not be established at this point.

Pulled 2 joints to 1780 m and established circulation, but pack off still occurred. Casing worked to 1780 m and circulation established in steps, casing could now be run to 1836 m. Casing run to 2050 m where there was little progress and it was decided to work casing upwards. Pulled to 2048 m but got 310 ton pull, which is the max limit for the BX-elevator. Casing was worked free with max pull of 350 ton and when casing arrived at surface it was discovered that 13 stop rings and 1 centralizer was missing. It was not possible to run casing to TD and the well was continued on the technical sidetrack T2.

B. Appendix B

All symptoms, the potential targets they are pointing at and the resulting path strengths are presented in the tables below. The tables are divided by main cause group. Further definition of some of the symptoms can be seen in Appendix B.5 and are obtained from the CREEK system.

B.1 Cuttings Accumulating

Table B.1: Symptoms, symbolic concepts and error resulting from Cuttings Accumulating

Symptom	Symbolic Concept	Strength 2	Symbolic Concept3	Strength 4	Symbolic Concept5	Strength3	Error Subclass/ Failure	Path Strength
Alternating Soft/Hard Fm.*	Erosion Of Soft Fm.	0,7	Cuttings Accumulating In Washout	0,5			Solids Settling	0,35
Cavings/Cuttings Plowing During Tripping**	Smooth Increased Drag	0,7					Solids Settling	0,7
Cuttings Storage Tanks Uavailable***	Cuttings Left In Hole	0,7	Wellbore Inc. > 30 Degree	0,9	Stationary Cuttings	0,9	Solids Settling	0,63
Decreased Mud Viscosity*	Mud/Fm. Fluids Interaction	0,7	Poor Hole Cleaning	0,7			Solids Settling	0,49
Difficult Re-Entry Conditions**	High Cuttings Concentration Preventing Re-Entry	0,7	Cuttings Accumulating In Washout	0,7			Solids Settling	0,7
Difficult Re-Entry Conditions**	Tight Hole After Still Stand	0,7	Periods Of Still Stand	0,9			Solids Settling	0,63

Drilling With High ROP*	Poor Cuttings Transport During Drilling	0,7	Poor Hole Cleaning	0,7			Solids Settling	0,49
Drilling With High WOB*	Bending Of BHA During Drilling	0,5	Poor Hole Cleaning	0,7			Solids Settling	0,35
Excessive Cuttings/Cavings Produced*	Mechanical/Hydraulic Erosion Of Wellbore Wall	0,7	Washout	0,9			Solids Settling	0,63
Excessive Cuttings/Cavings Produced*	High Cuttings Concentration	0,5	Cuttings Left In Hole	0,9			Solids Settling	0,45
Excessive Cuttings/Cavings Produced*	Mechanical/Hydraulic Erosion Of Wellbore Wall	0,7	Washout	0,9	Cuttings Accumulating In Washout	0,9	Solids Settling	0,567
Formation Fluids/Mud Interaction**	Reduced Mud Viscosity	0,7	Poor Cuttings Transport	0,9			Solids Settling	0,63
High DLS*	High DLS At Wellbore Inclinaton > 60 Degree	0,9	Stationary Cuttings	0,5			Solids Settling	0,45
High MW - Ppore**	Overbalanced Wellbore Pressure	0,9	Filtercake Build-Up	0,5			Increasing Filtercake	0,45
Increased Drag*	Smooth Increased Drag	0,5					Solids Settling	0,5
Increased Mud Solids Content**	Poor Cuttings Transport	0,5	Poor Hole Cleaning	0,7			Solids Settling	0,35
Increased SPP*	Restricted Circulation	0,7	High Cuttings Concentration	0,7			Solids Settling	0,49
Increased Torque After Still Stand*	Restricted Rotation	0,9	Filtercake Build-Up	0,9			Increasing Filtercake	0,81
Increased Torque*	Wellbore Inc. > 30 Degree	0,9	Stationary Cuttings	0,7			Solids Settling	0,63
Increased Torque*	String Torqued Up	0,7	High Cuttings Concetration	0,9			Solids Settling	0,63
Increasing SPP*	Restricted Circulation	0,7	High Cuttings Concentration	0,7			Solids Settling	0,49

Less Cuttings On Shaker*	Less Cuttings Produced At Wellbore Inc. > 30 Degree	0,9	Stationary Cuttings	0,9			Solids Settling	0,81
Long Period Of Stand Still*	Static Well	1,0	Vertical/Horizontal Well	0,9	Filtercake Build-Up	0,9	Increasing Filtercake	0,81
Long Period Of Stand Still*	Static Well	1,0	Horizontal Well	0,7	Stationary Cuttings	0,9	Solids Settling	0,63
Long Period Of Stand Still*	Static Well	1,0	Vertical Well	0,5	Stationary Cuttings	0,9	Solids Settling	0,45
Long Periods Of Circulation*	Hydraulic Erosion Of Wellbore Wall	0,9	Washout	0,9			Solids Settling	0,81
Long Well*	High Cuttings Concentration	0,5	Stationary Cuttings	0,7			Solids Settling	0,35
Low Flow Rate*	Poor Cuttings Transport	0,9	Poor Hole Cleaning	0,9			Solids Settling	0,81
Low RPM***	RPM < 120	0,9	Poor Hole Cleaning	0,7			Solids Settling	0,63
Low RPM***	RPM < 70	0,9	Poor Hole Cleaning	0,7			Solids Settling	0,63
Mud Pumps Down During Drilling***	Poor Cuttings Transport	0,7	Poor Hole Cleaning	0,7			Solids Settling	0,49
OP After Flow Check*	Filtercake Build-Up During Flow Check	0,9					Increasing Filtercake	0,9
Overpull At Area Of Alternating Hard/Soft Fm.*	Erosion Of Soft Fm.	0,7	Washout	0,5			Solids Settling	0,35
Overpull At Wellbore Inclinaton > 30 Degree*	High Cuttings Concentration	0,9	Stationary Cuttings In Wellbore	0,9			Solids Settling	0,9
Overpull Straight After Flow Check*	Filtercake Build-Up During Flow Check	0,9					Increasing Filtercake	0,9
String Stalled Out At High Wellbore Inc.**	Wellbore Inc. > 30 Degree	0,7	Stationary Cuttings	0,7			Solids Settling	0,49
Sudden Increased ROP During Drilling*	Drilling Soft Formation	0,5	Erosion Of Soft Fm.	0,7	Washout	0,7	Solids Settling	0,245
Took Weight At High Wellbore Inc.*	Wellbore Inclinaton > 30 Degree	0,7	Stationary Cuttings	0,7			Solids Settling	0,49

Unrestricted Annular Flow*	Normal Pump Pressure	0,7	Periods Of Still Stand	0,9			Increasing Filtercake	0,7
Very Aggressive BHA**	Mechanical/Hydraulic Erosion Of Wellbore Wall	0,7	Washout	0,7			Solids Settling	0,49
Very Aggressive BHA**	Mechanical/Hydraulic Erosion Of Wellbore Wall	0,5	Increased LGSC	0,5			Solids Settling	0,25
Wellbore Inc. > 60 Degree*	High Cuttings Concentration At High Wellbore Inc.	0,7	Stationary Cuttings	0,5			Solids Settling	0,35
Wellbore Inc. > 60 Degree*	Stationary Cuttings	0,7	Periods Of Still Stand	0,5	Filtercake Build-Up	0,9	Increasing Filtercake	0,315
Wellbore Inc. > 60 Degree*	Alternating Soft/Hard Fm. At High Wellbore Inc.	0,7	Washout	0,5			Solids Settling	0,35

B.2 Mechanically Unstable Wellbore

Table B.2: Symptoms, symbolic concepts and error resulting from Mechanically Unstable Wellbore

Symptom	Symbolic Concept	Strength2	Symbolic Concept3	Strength 4	Symbolic Concept5	Strength 3	Error Subclass/Failure	Path Strength
Angular Cavings Produced*	Angular Cavings From Fractured Formations	0,9	Low MW-Pfrac	0,5	Unstable Formation	0,9	Enlarged Wellbore	0,41
Unrestricted Annular Flow*	Normal Pump Pressure	1,0	Alternating Soft/Hard Fm.	0,7	Ledges	0,7	Enlarged Wellbore	0,49
Alternating Soft/Hard Fm.*	Erosion Of Soft Fm.	0,5					Enlarged Wellbore	0,7
Alternating Soft/Hard Fm.*	Erosion Of Soft Fm.	0,5	Ledges	0,9			Enlarged Wellbore	0,45
Alternating Soft/Hard Fm.*	Drilling Hard Stringers	0,7	Low Cuttings Bed Height	0,5			Enlarged Wellbore	0,7
Backreaming/ Reaming Passed Restriction**	Mechnical Erosion During Reaming	0,7	Ledges	0,7			Enlarged Wellbore	0,7
Backreaming/ Reaming Passed Restriction**	Increased ECD During Reaming	0,9	Excessive Wellbore Stress	0,5			Lost Circulation	0,45
Backup Equipment Not Available***	Undergauged BHA Components RIH	0,7					Undergauged Hole	0,7
Blocky Cavings Produced*	Blocky Cavings Produced From Excessive Wellbore Stress	0,9	Ledges	0,9			Enlarged Wellbore	0,81
Cavings Production During UBD*	Cavings Produced When Mud Penetrates Fm.	0,7	Low MW-Ppore	0,5			Enlarged Wellbore	0,35
Cavings/Cuttings Plowing During Tripping**	Spot Of Overpull Moving Up Hole During Tripping	0,7					Enlarged Wellbore	0,7
Cuttings Storage Tanks Uavailable***	Wainting On Weather For New Tanks	0,5	Collapsing Hole	0,5			Enlarged Wellbore	0,25

Decreased ROP During Drilling*	ROP Decreases When Drilling Hard Stringers	0,5	Erosion Of Soft Fm.	0,7			Enlarged Wellbore	0,35
Difficult Re-Entry Conditions**	Alternating Soft/Hard Fm. Preventing Re-Entry	0,9	Ledge	0,7			Enlarged Wellbore	0,9
Difficult Re-Entry Conditions**	Intersecting Faults Preventing Re-Entry	0,7	Ledge	0,7			Enlarged Wellbore	0,49
Drill String Vibrations**	Excessive Wellbore Stress	0,5	Weakened Wellbore	0,5			Enlarged Wellbore	0,25
Drill String Vibrations**	Mechanical Erosion Of Wellbore Wall	0,7	Pack Off	0,9			Enlarged Wellbore	0,441
Drilling With High ROP*	Increased ECD During Drilling	0,5	Induced Fractures	0,7			Lost Circulation	0,35
Drilling With High WOB*	High WOB When Drilling Hard Stringers	0,5	Bit Stick-Slip	0,5			Enlarged Wellbore	0,25
Drilling With WBM*	Increased Wellbore Stress	0,5	Increased Fracture Pressure	0,5			Lost Circulation	0,25
Dropping Inclination*	Erratic Directional Control	0,7					Enlarged Wellbore	0,7
Excessive Cuttings/Cavings Produced*	Cavings Production Due To Unstable Formation	0,9					Enlarged Wellbore	0,9
Excessive Cuttings/Cavings Produced*	Wellbore Pack Off	0,9	ledges	0,9			Enlarged Wellbore	0,81
Excessive Cuttings/Cavings Produced*	Cavings Due To Low MW-Ppore	0,7	Borehole Breakout	0,7			Enlarged Wellbore	0,49
Excessive Cuttings/Cavings Produced*	Mechanical/Hydraulic Erosion	0,7	Ledges	0,7			Enlarged Wellbore	0,49
Fm. Fluids/Mud Interaction**	Fm. Water Sucked Into Drilling Mud	0,5	Weakened Wellbore	0,5	Brittle Wellbore Wall	0,9	Enlarged Wellbore	0,225
Gain In Mud Pits With Pumps Off*	Mud Loss Before Gain	0,9					Ballooning Well	0,9

Hard Stringers*	Fm. Above/Below Eroded	0,7					Enlarged Wellbore	0,7
Hard Stringers*	High Pack Off Tendency Of Hard. Fm	0,5	Unstable Formation	0,7			Enlarged Wellbore	
Hard Stringers*	Interbedded Hard/Soft Fm.	0,7	Erosion Of Soft Fm.	0,5			Enlarged Wellbore	0,7
High SPP*	Increased Wellbore Pressure	0,9	Increased ECD	0,7			Lost Circulation	0,7
High Surge Pressure**	Excessive Wellbore Stress	0,7	Weakened Wellbore	0,9			Enlarged Wellbore	0,7
High Surge Pressure**	High Tripping Velocity	0,5	Increased Wellbore Pressure	0,7			Lost Circulation	0,35
High Swab Pressure**	Excessive Wellbore Stress	0,9	Weakened Wellbore	0,7			Enlarged Wellbore	0,63
Increased Drag*	Increased Drag After Recent Cavings Prod.	0,9	Collapsing Hole	0,9			Enlarged Wellbore	0,81
Increased Drag*	Sudden Increased Drag	0,5	Ledges	0,7			Enlarged Wellbore	0,5
Increased Drag*	Sudden Increased Drag	0,5	Unstable Formation	0,9			Enlarged Wellbore	0,45
Increased Mud Solids Content*	Increased Mud Viscosity	0,5	Induced Fracture	0,5			Lost Circulation	0,25
Increased SPP*	Restricted Circulation	0,9	Increased ECD	0,5	Induced Fractures	0,7	Lost Circulation	0,315
Increased Torque*	String Torqued Up	0,7	Hard Stringers	0,5			Enlarged Wellbore	0,49
Long Period Of Stand Still*	Static Well During Still Stand	1,0	Vertical/Horizontal Well	0,5	Collapsing Hole	0,9	Enlarged Wellbore	0,45
Long Well*	Increasing ECD	0,9	Weakened Wellbore	0,5	Collapsing Hole	0,9	Enlarged Wellbore	0,405
Long Well*	Increasing ECD	0,5	Induced Fractures	0,7			Lost Circulation	0,35
Low MW-Pfrac**	High MW	0,7	Induced Fractures	0,5			Lost Circulation	0,35
Low MW-Pfrac**	Increased BHP	0,7					Lost Circulation	0,7
Low MW-Pfrac**	Increased BHP	0,7	Borehole Breakout	0,9	Angular Shaped Cavings	0,9	Enlarged Wellbore	0,567

Low MW-Pfrac**	Increased BHP	0,9	Increased ECD	0,5			Lost Circulation	0,45
Non-PDC Cuttings Produced*	Mechanical/Hydraulic Erosion Of Wellbore Wall	0,9	Unstable Formation	0,9			Enlarged Wellbore	0,81
Overpull At Area Of Alternating Hard/Soft Fm.*	Overpull At Depth Of BHA Component	0,9	Ledges	0,9			Enlarged Wellbore	0,81
Overpull At Area Of Alternating Hard/Soft Fm.*	Erosion Of Soft Fm.	0,7	Ledges	0,7			Enlarged Wellbore	0,49
Overpull At Shallow Depth*	Recent Cavings Production Before Overpull	0,7	Brittle Fm.	0,7	Unstable Formation	0,9	Enlarged Wellbore	0,441
Pack Off After Increasing MW*	Increased SPP	0,7	Induced Fractures	0,7			Lost Circulation	0,49
Pack Off After Increasing MW*	Pack Off	0,5	Collapsing Hole	0,9			Enlarged Wellbore	0,25
Pack Off During Drilling Of Hard Stringers*	Fm. Above/Below Stringers Eroded	0,5					Enlarged Wellbore	0,5
Pack Off During Rotation And Circulation*	Mechanical/Hydraulical Erosion During Rot. And Circ.	0,9	Ledges	0,9			Enlarged Wellbore	0,81
Pack Off During Rotation And Circulation*	Mechanical/Hydraulical Erosion During Rot. And Circ.	0,9	Unstable Formation	0,9			Enlarged Wellbore	0,81
Splintery Cavings Produced During UBD*	Shale Pack Off	0,7					Enlarged Wellbore	0,7
Sudden Increased ROP During Drilling*	Natural Fractured Zones Drilled	0,5					Lost Circulation	0,5
Sudden Increased ROP During Drilling*	Soft Formation Drilled	0,5	Erosion Of Soft Fm.	0,7	Ledges	0,7	Enlarged Wellbore	0,245

Tabular Cavings Produced*	Faults And Pre-Excisting Fractures Creating Tabular Cavings	0,9	Unstable Formation	0,9			Enlarged Wellbore	0,81
Took Weight After Recent Cavings Production*	Cavings Due To Unstable Formation	0,7	Collapsing Hole	0,9			Enlarged Wellbore	0,63
Took Weight At Area Of Alt. Hard/Soft Fm.*	Took Weight After Recent Caving Production	0,9	Erosion Of Soft Fm.	0,7	Ledges	0,7	Enlarged Wellbore	0,441
Undergauged BHA Components**	Mechanical Erosion Of Wellbore Wall	0,7	Ledges	0,7			Enlarged Wellbore	0,49
Very Aggressive BHA**	Mechanical/Hydraulic Erosion	0,7					Enlarged Wellbore	0,7

B.3 Chemically Unstable Wellbore

Table B.3: Symptoms, symbolic concepts and error resulting from Chemically Unstable Wellbore

Symptom	Symbolic Concept	Strength2	Symbolic Concept3	Strength 4	Symbolic Concept5	Strength3	Error Subclass/Failure	Path Strength
Shallow Depth*	Shallow Shale Section	0,5	High Montmorillonite Content	0,5	Water/Shale Interaction	0,9	Reactive Shale	0,225
Bit Balling**	Shallow Shale Section	0,9	Shale/Water Interaction	0,9			Reactive Shale	0,81
Cuttings Storage Tanks Uavailable***	Waiting On New Tanks	0,7	Time Dependent Deformation	0,5			Reactive Shale	0,35
Difficult Re-Entry Conditions**	Shallow Shale Preventing Re-Entry	0,5	Time Dependent Deformation	0,5			Reactive Shale	0,5
Drilling With WBM*	WBM At Shallow Depths	0,5	Water/Shale Interaction	0,7			Reactive Shale	0,35
Gumbo Shale Produced*	Water/Shale Interaction	0,9					Reactive Shale	0,9
Long Open Hole Time*	Long Shale Exposure Time	0,9	Shale/Water Interaction	0,9			Reactive Shale	0,81
Overpull At Shallow Depth*	Shallow Shale Section	0,7	High Montmorillonite Content	0,7	Water/Shale Interaction	0,9	Reactive Shale	0,441
Overpull Straight After Flow Check*	Shallow Shale Section	0,7					Reactive Shale	0,7
Increased SPP*	Restricted Circulation	0,7	Shallow Shale Pack Off	0,9			Reactive Shale	0,63
Shale Formation Pack Off*	Increased SPP	0,7					Reactive Shale	0,7
Took Weight At Shallow Depth*	Shallow Depth	0,9	Water/Shale Interaction	0,7			Reactive Shale	0,63
Increased Torque*	Shallow Shale Section	0,7					Reactive Shale	0,7

B.4 Local Dogleg

Table B.4: Symptoms, symbolic concepts and error resulting from Local Dogleg

Symptom	Symbolic Concept	Strength2	Symbolic Concept3	Strength4	Error Subclass/Failure	Path Strength
Difficult Re-Entry Conditions**	Tight Spot	0,5			Dogleg	0,5
Alternating Soft/Hard Fm.*	Erosion Of Soft Fm.	0,5			Dogleg	0,5
High DLS*	High Drag During Tripping	0,9			Dogleg	0,9
High DLS*	Alternating Soft/Hard Fm.	0,9	Erosion Of Soft Fm.	0,5	Dogleg	0,45
Increased Drag*	Excessive Drag During Tripping	0,7			Dogleg	0,7
Took Weight At High DLS*	Dogleg	0,7			Dogleg	0,7
Unrestricted Annular Flow At Tight Spot*	Dogleg	0,9			Dogleg	0,9

B.5 Definition of symptoms

Long Stand Still Time

$$Def.: t - t_{moves-string} > 0,5 - -2h$$

High DLS

$$Def.: DLS > 3\ degree/30\ m$$

High Drag

$$\frac{drag-1}{drag-100} > 1,2$$

Drag – 10 = average drag during hoisting last 10 h

Low Flow Rate, q

$$Def.: Low\ q\ for\ more\ than\ 15\ min$$

Have to be related to the excepted or normal q

Low RPM

$$RPM\ for\ hole > 9" < 120RPM$$

$$RPM\ for\ hole < 8,5" < 70RPM$$

Lost Circulation

If the pressure in the well exceeds the fracture pressure, lost circulation will occur.

$$p_{pore} < p_{well} < p_{frac}$$

Fracturing of the reservoir, and lost circulation, occur when:

$$p_{frac} - p_{pore} < p_{well}$$

High Mud Viscosity

$$PV > 30 - -40cP$$

High WOB

$$\frac{WOB - 1}{WOB - 30} > 1,2$$

WOB-30 = average WOB during the last 30 m drilled

Low WOB

$$\frac{WOB - 1}{WOB - 30} < 0,8$$

WOB-30 = average WOB during the last 30 m drilled

Low Bottomhole Pressure

$$p_{pore} > p_{well}$$

High RPM

$$\frac{RPM - 1}{RPM - 30} > 0,8$$

RPM-30 = average RPM during the last 30 m drilled

Increased ROP

$$\frac{ROP - 5}{RPM - 30} > 1,1$$

ROP-30 = average ROP during the last 30 m drilled

Low ROP

$$\frac{ROP-1}{RPM-30} < 0,8$$

ROP-30 = average ROP during the last 30 m drilled

Long Well

$$Def. :> 5000m$$

Long Backreaming Time

$$Def. :> 1hour$$

Shallow Depth

$$Def. :> 2500m$$

Very Low EFC-ECD Difference

$$Difference < 0,05kg/l$$

Took Weight

$$\frac{Weight}{Weight-100} < 0,7 = Instantaneous\ weight\ during\ RIH$$

C. Appendix C

C.1 Calculation of Main Restriction Cause

The calculation of the explanatory strength of each restriction event can be seen in table C.1.

Table C.1: Cases of HKL-restrictions and their symptoms

Case	Symptom	Strength	Path Strength	Main Cause	Expl. Strength
2	OP After Flow Check	0,9	0,9	1 c.	0,59
	Restricted Rotation	$0{,}9 \cdot 0{,}9$	0,81	1 c.	
	Wellbore Inc. > 60	$0{,}7 \cdot 0{,}5 \cdot 0{,}9$	0,32	1 c.	
	Wellbore Inc. > 60 ^{o}	$0{,}7 \cdot 0{,}5$	0,35	1.a	0,29
	Overbalanced Pressure	$0{,}9 \cdot 0{,}5$	0,45	1.c	
	Unrestr. Ann. Flow	$0{,}7 \cdot 0{,}9$	0,63	4 a.	0,12
	Unrestr. Ann. Flow	0,7	0,7	1.c	
	Mud Pumps Down	$0{,}7 \cdot 0{,}7$	0,49	1.a	
	Cavings/Cuttings Plowing	0,7	0,7	1.a	
3	Wellbore Inc. > 60 ^{o}	$0{,}7 \cdot 0{,}5 \cdot 0{,}9$	0,32	1 c.	0,1
	Wellbore Inc. > 60 ^{o}	$0{,}7 \cdot 0{,}5$	0,35	1.a	0,49
	Took Weight At High Wellbore Inc.	$0{,}9 \cdot 0{,}9$	0,81	1 a.	
	High DLS	0,7	0,7	4 a.	0,2
	String Stalled Out	$0{,}7 \cdot 0{,}7$	0,49	1 a.	
	Reaming	0,7	0,7	2 a.	0,2

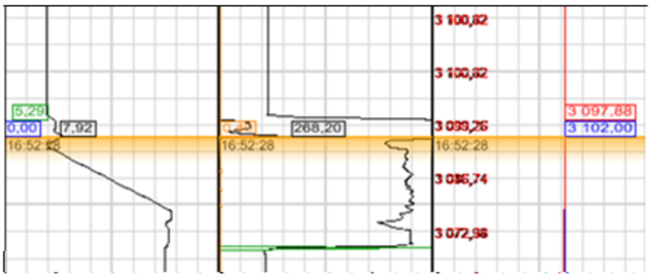
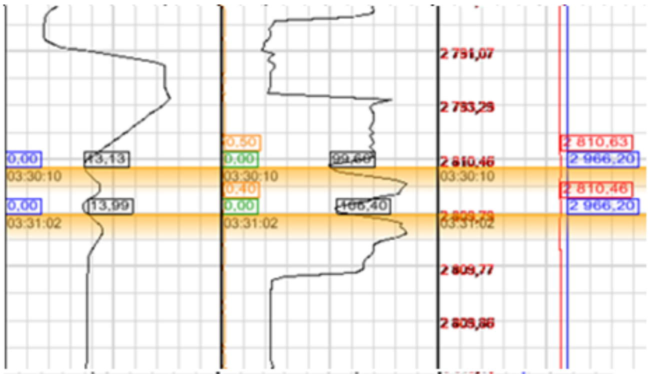
Case	Symptom	Strength	Path Strength	Main Cause	Expl. Strength
4	Altern. Soft/Hard Fm.	0,5 · 0,9	0,45	2 a.	0,63
	Altern. Soft/Hard Fm.	0,5 · 0,7	0,35	1 b.	0,16
	Altern. Soft/Hard Fm.	0,5 · 0,9	0,35	4 b.	0,21
	Wellbore Inc. > 60 ^{o}	0,7 · 0,5	0,35	1.b	
	Hard Stringers	0,7	0,7	2 a.	
	Hard Stringers	0,9 · 0,5	0,45	4 b.	
	Unrestr. Ann. Flow	0,7 · 0,7	0,49	2 a.	
	Undergauged BHA Comp.	0,7 · 0,7	0,49	2 a.	
	Drill String Vib.	0,5 · 0,5	0,25	2 a.	
7	Hard Stringers	0,9 · 0,5	0,45	4 b.	0,14
	Hard Stringers	0,5 · 0,7	0,35	2 b.	0,14
	Hard Stringers	0,7	0,7	2 a.	0,56
	Altern. Soft/Hard Fm.	0,5 · 0,9	0,45	2 a.	
	Altern. Soft/Hard Fm.	0,5 · 0,7	0,35	1 b.	0,16
	Altern. Soft/Hard Fm.	0,5 · 0,9	0,35	4 b.	
	Reaming Down	0,7 · 0,7	0,49	2 a.	
	Took Weight At Area Of Hard/Soft Fm.	0,7 · 0,7 · 0,9	0,44	2 a.	
	Pack Off During Rotation And Circ.	0,7 · 0,7	0,49	2 b.	
	Pack Off After Rot./Circ.	0,9 · 0,9	0,81	2 a.	
	Excessive Cut./Cav.	0,7 · 0,9	0,63	1 b.	
	Excessive Cut./Cav.	0,7 · 0,7	0,49	2 a.	
12	Blocky Cavings	0,9 · 0,9	0,81	2 b.	0,62
	Cav./Cutt. Plowing	0,7	0,7	2 b.	
	Cav./Cutt. Plowing	0,7	0,7	1 a.	0,12
	Excessive Cutt./Cav.	0,9	0,9	2 b.	
	Excessive Cutt./Cav.	0,9 · 0,9	0,81	2 b.	
	Fm. Fluid/Mud Interact.	0,9	0,9	3 a.	0,26
	Fm. Fluid/Mud Interact	0,5 · 0,5 · 0,9	0,23	2 b.	
	Shallow Depth	0,9 · 0,9 · 0,7	0,56	3 a.	
13	Excessive Cutt./Cav.	0,9	0,9	2 b.	0,78
	Excessive Cutt./Cav.	0,9 · 0,9	0,81	2 b.	
	Non-PDC Cuttings	0,9 · 0,5	0,45	2 b.	
	OP At Shallow Depth	0,9 · 0,7 · 0,7	0,44	2 b.	
	OP At Shallow Depth	0,7 · 0,9 · 0,7	0,44	3 a.	0,22
	Increased Drag	0,7	0,7	2 b.	
	Took Weight At Area of Hard/Soft Fm.	0,5 · 0,9	0,45	2 b.	
	Blocky Cavings	0,9 · 0,9	0,81	2 b.	
	Fm. Fluid/Mud Inertact.	0,9	0,9	3 a.	
	Fm. Fluid/Mud Inertact.	0,5 · 0,5 · 0,9	0,23	2 b.	

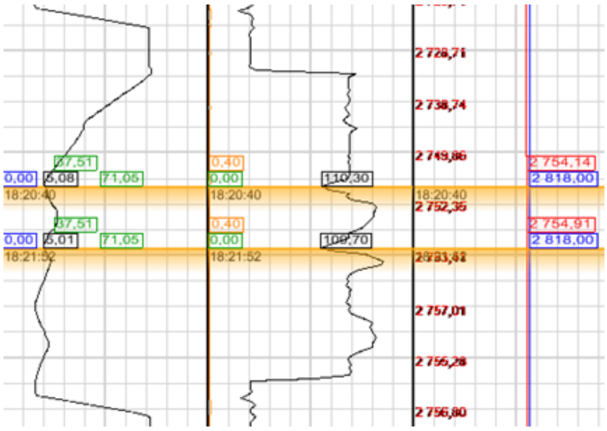
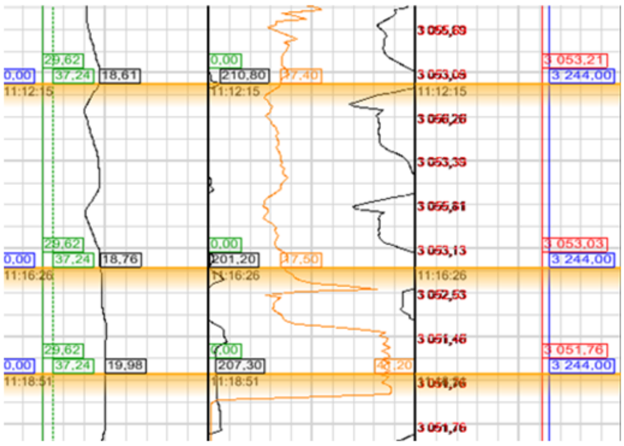
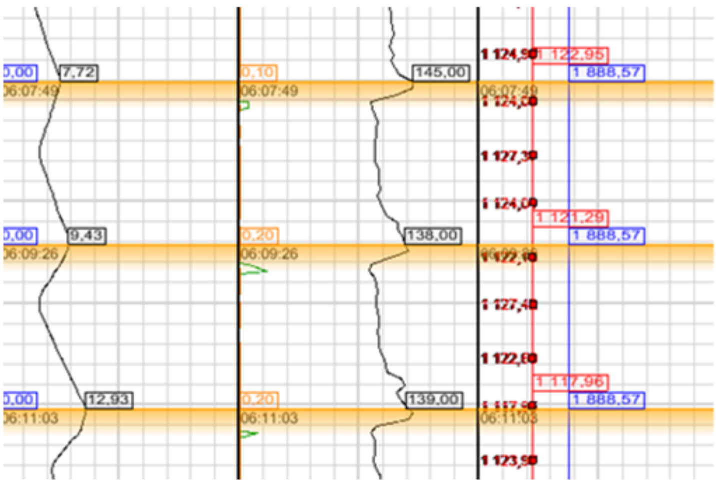
Case	Symptom	Strength	Path Strength	Main Cause	Expl. Strength
16	Pack Off During Drilling Of Hard Stringers	0,5	0,5	2 a.	0,49
	Pack Off	$0{,}9 \cdot 0{,}5$	0,45	2 b.	0,42
	Non-PDC Cuttings	$0{,}9 \cdot 0{,}5$	0,45	2 b.	
	Cav./Cutt. Plowing	0,7	0,7	2 b.	
	OP At Depth Of BHA Comp.	0,9	0,9	2 a.	
	Overpull	$0{,}7 \cdot 0{,}9 \cdot 0{,}7$	0,44	3 a.	0,09
	Altern. Soft/Hard Fm.	$0{,}5 \cdot 0{,}9$	0,45	2 a.	
	Hard Stringers	$0{,}5 \cdot 0{,}7$	0,35	2 b.	
	Hard Stringers	0,7	0,7	2 a.	
18	OP At Wellbore Inc. $> 60\ ^o$	$0{,}5 \cdot 0{,}9$	0,45	1 a.	0,28
	Increased Drag	0,7	0,7	4 a.	0,56
	High DLS	0,7	0,7	4 a.	
	Wellbore Inc. $> 60\ ^o$	$0{,}9 \cdot 0{,}9$	0,81	1.a	
	Wellbore Inc. $> 60\ ^o$	$0{,}7 \cdot 0{,}5$	0,35	1.b	0,16
	Altern. Soft/Hard Fm.	0,5	0,5	4 a.	
	Altern. Soft/Hard Fm.	$0{,}5 \cdot 0{,}7$	0,35	1 b.	
	Unrestr. Ann. Flow	$0{,}7 \cdot 0{,}9$	0,63	4 a.	0,56
19	Wellbore Inc. $> 60\ ^o$	$0{,}5 \cdot 0{,}7$	0,35	1 b.	0,1
	Wellbore Inc. $> 60\ ^o$	$0{,}5 \cdot 0{,}7$	0,35	1 a.	0,57
	Cav./Cutt. Plowing	0,7	0,7	1 a.	
	Took Weight	$0{,}7 \cdot 0{,}7$	0,49	1 a.	
	Took Weight	$0{,}7 \cdot 0{,}7$	0,49	4 a.	0,33
	High DLS	0,7	0,7	4 a.	
	Cuttings Storage Tanks Unavailable	$0{,}9 \cdot 0{,}9 \cdot 0{,}7$	0,57	1 a.	
21	Wellbore Inc. $> 60\ ^o$	$0{,}5 \cdot 0{,}7$	0,35	1 b.	0,44
	Wellbore Inc. $> 60\ ^o$	$0{,}5 \cdot 0{,}7$	0,35	1 a.	0,41
	Alt. Soft/Hard Fm.	$0{,}5 \cdot 0{,}9$	0,45	2 a.	0,14
	Alt. Soft/Hard Fm.	$0{,}5 \cdot 0{,}7$	0,45	1 b.	
	Overpull	$0{,}9 \cdot 0{,}7 \cdot 0{,}7$	0,44	1 b.	
	Excessive Cutt./Cav.	$0{,}7 \cdot 0{,}7$	0,49	2 a.	
	Excessive Cutt./Cav.	$0{,}7 \cdot 0{,}9$	0,63	1 b.	
	Excessive Cutt./Cav.	$0{,}5 \cdot 0{,}9$	0,45	1 a.	
	Cuttings Storage Tanks Unavailable	$0{,}9 \cdot 0{,}9 \cdot 0{,}7$	0,57	1 a.	

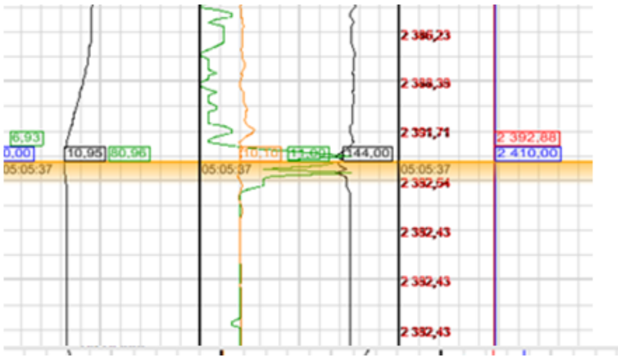
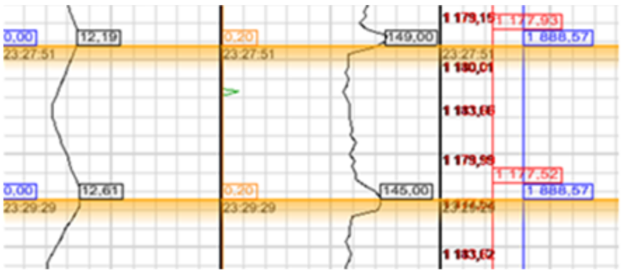
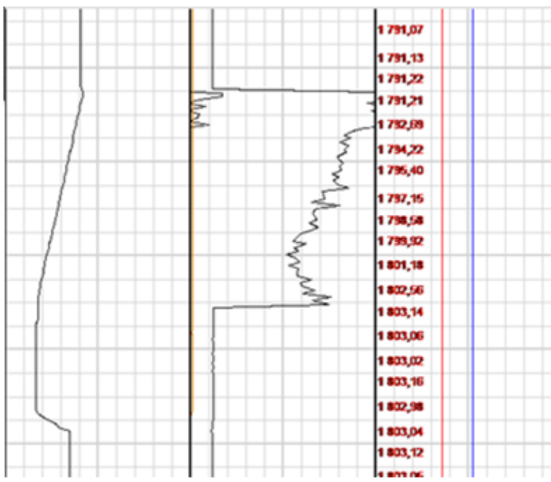
C.2 HKL signature of each case

Table C.2 presents the HKL signature of each restriction case. All HKL restrictions snaps are taken at a 10 minute interval.

TABLE C.2: HKL signature of each case

Case	HKL Signature	
2		90 ton OP after flow check
3		Took weight at high wellbore inclination, reamed passed area

Case	Symptom	
4		Took weight twice at same depth
7		Worked through area of overpull
12		Spot of OP moving upwards in the well during tripping

Case	Symptom
14	 Tight spot. Well packed off, SPP increases — : WOB — : Torque
16	 Fixed spot of OP, at area of hard stringers
18	 Working through area of high DLS
19	 Tight spot during RIH, at high wellbore inclination