Analytical solution for stuck pipe problems based on worldwide company practices

Master Thesis

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EIDESSTATTLICHE ERKLÄRUNG

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

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

Leoben, June 2017

(Date)

Ivan Drašković

I want to dedicate this work to my grandparents Đuro S. and Danica Drašković, and to my uncle Vladimir Bato Vukčević, whose heart stopped beating not so long ago.

Acknowledgment

First of all, I want to express my deepest gratitude to my parents Ljiljna and Dušan, my brother Marko Drašković and my grandmother Vukosava Mančić. They have supported me tirelessly throughout my life and during my studies at the University of Leoben.

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Abstract

Demands for natural resources, primarily for oil and gas in the world, are not decreasing. But on the other hand, in order to fulfil the requirements of the market, drilling limits are being pushed, resulting in problems becoming more frequent.

One of the most frequent and widespread problems in the oil industry is a stuck pipe, which requires a lot of time and effort to release the stuck pipe string, with an outcome which is always uncertain.

The appropriate response to the actual stuck pipe condition is sometimes the key to defining the success of further stuck pipe releasing activities. Keeping in the mind that the chances of releasing a stuck pipe string decreases over time, misjudging the stuck pipe mechanism and applying an inappropriate freeing procedure can further complicate the situation and make releasing the drill string uncertain.

At the beginning of this work an overview of all the stuck pipe mechanisms is given, as well as the deviation in the operational parameters in regard to the stuck pipe mechanisms before and at the moment of the stuck pipe condition. Subsequently, all of the selected companies' freeing procedures will be presented.

This thesis continues with an analytical model whose purpose is deriving general freeing procedures with the sequence of operations for the group of the three main types of stuck pipe mechanisms: mechanical sticking and wellbore geometry, differential sticking and the solid induced pack-off. The quality of the derived general freeing procedures is directly related to the amount of available freeing procedures for each stuck pipe mechanism, individually, which belongs to the aforementioned group.

In order to be able to use the model, a coding system is introduced**,** then, based on the amount of collected freeing procedures**,** the threshold values are estimated. After this the function average and standard deviation will be introduced and the final result will be the general freeing procedure.

When the freeing procedure is finally obtained, each code is replaced with the certain operation, which should be performed when a stuck pipe occurs.

Finally, the presented model results in obtaining the general freeing procedures, from which one of these should be chosen according to the particular stuck pipe mechanism, which has been tested on an artificial data set created by the author, where its validity should be confirmed.

Kurzfassung

Die Nachfrage nach Rohstoffen, insbesondere Erdöl und Erdgas, wird in absehbarer Zeit nicht abnehmen. Um die Nachfrage auf den Märkten bedienen zu können, werden die technischen Grenzen des Bohrens ausgereizt, mit dem Resultat, dass es häufiger zu Problemen kommt.

Das Festwerden des Bohrstranges ist eines der häufigsten und verbreitetsten Probleme in der Ölindustrie, dessen Behebung mit großem Aufwand und Unsicherheiten verbunden ist.

Die angemessenen Maßnahmen im Falle des Festwerdens zu treffen, ist der Schlüssel zum Erfolg von weiterführenden Aktivitäten zum Befreien des Bohrstranges. Da die Erfolgswahrscheinlichkeit abnimmt, je länger das Gestänge festsitzt, kann eine Fehleinschätzung der Situation und das Anwenden von ungeeigneten Maßnahmen zur Befreiung des Stranges die Situation verschlimmern.

Am Beginn der Arbeit wird ein sowohl Überblick über die verschiedenen Mechanismen des Festwerdens selbst, als auch über das Verhalten wichtiger Parameter kurz vor und im Moment des Festwerdens. Anschließend werden die Standardprozeduren zum Befreien des Bohrstranges einiger ausgewählter Firmen diskutiert.

Im nächsten Abschnitt wird ein analytisches Modell vorgestellt, das den Zweck hat generelle Prozeduren zum Befreien für die drei Hauptarten des Festwerdens abzuleiten: Mechanisches Stecken auf Grund der Bohrlochgeometrie, Festwerden durch Differenzdruck und durch Bohrklein induziertes Abpacken. Die Qualität der grundlegenden Prozeduren hängt direkt mit der Menge an verfügbaren Befreiungsprozeduren für den jeweiligen Mechanismus ab.

Um das Modell benutzen zu können, wird ein Codierungssystem eingeführt und anschließen, basierend auf den möglichen Prozeduren, ein Schwellwert geschätzt. Danach wird mit Hilfe von Standardabweichung und Mittelwert die geeignetste Methode zum Befreien ermittelt. Anschließend wird jeder Code durch die jeweiligen Verfahrensschritte ersetzt, die, in dieser ermittelten Reihenfolge durchgeführt, die besten Erfolgschancen zum Befreien des Bohrstranges bieten.

Abschließend erhält man durch das präsentierte Modell generelle Prozeduren zum Befreien des Bohrstranges, von welchen eine passende gewählt und seine Richtigkeit an einem vom Autor erstellten Datensatz bestätigt werden soll.

Contents

1 Introduction

Stuck pipe is a general term which describes the problem of losing the ability of the drilling string to rotate and move up or down. It is important to note that a stuck pipe is a global problem with a frequency of occurrence of about 25 % of the total non-productive time [(1)]. Due to this reason, it is not surprising that individuals and companies are making an effort to find appropriate solutions for reducing its frequency and the adverse outcomes as much as possible.

Stuck pipe problems can be classified into three main categories, these are: mechanical sticking and wellbore geometry, differential sticking and solid induced pack-off. Each of these includes distinct types of stuck pipe mechanisms, which sometimes confuses the driller while determining the appropriate freeing procedure, based on the stuck pipe mechanism.

1.1 Scope of the study

A large number of different freeing procedures for each stuck pipe mechanism are written in company manuals as a part of their standard project documentation. Each procedure guarantees a certain degree of success, although sometimes the same stuck pipe mechanisms can be very different in regard to the sequence of operations which should be applied at the moment of the stuck pipe situation.

Keeping in mind that time is the limiting factor which determines the success of the freeing operation, there is a small margin for error. For this reason, the scope of this study is finding the appropriate method to link similar procedures for different stuck pipe mechanisms, as much as possible, while also not reducing their effectiveness. This should result in obtaining a general freeing procedure for the three main types of stuck pipe mechanisms, while simultaneously eliminating the possibility for mistakes regarding the type of freeing procedure which should be applied (at the rig site) at the moment of the stuck pipe situation.

Tasks during the project:

- Find as many different companies' freeing procedures as possible
- The obtained data will be analysed, then once the relationships are found, a model will be developed which should help (based on the preceding information) to derive a general freeing procedure for the three main types of stuck pipe mechanism
- All deviations from the model, in regard to the introduced assumptions and additional analysis performed, should be noted down

1.2 Structure of the thesis

In this chapter-introduction a short overview of all the work is briefly outlined in regard to the structure of the thesis, stuck pipe mechanisms, freeing procedures and analytical model derivation.

The second chapter provides a detailed explanation of the all stuck pipe mechanisms, regarding their mechanical characteristics, uniqueness and the location of their appearance.

The third chapter presents the different freeing procedures for all the stuck pipe mechanisms which were collected, including their operational parameter deviation before and at the moment of the stuck pipe.

The forth chapter is the main part of the thesis, where the analytical model with its phases, are explained in detail.

The fifth chapter covers the effectiveness of the application of the selected general freeing procedure based on the particular cause of the stuck pipe mechanism, which is then tested on artificial data creation.

The last chapters present the obtained results in conclusion and also recommendations for further (future) activities.

2 Stuck pipe mechanisms

A large number of different stuck pipe mechanisms exist, however, all of them can be organised into the one of the following categories:

- Mechanical sticking and wellbore geometry
- Differential sticking
- Solid induced pack-off

Determination of the appropriate mechanisms has a large impact on the success of the freeing procedure selected. Accordingly, each stuck pipe mechanism which belongs to one of these three categories above, will be clearly explained below.

2.1 Mechanical sticking and wellbore geometry

Stuck pipe, due to mechanical sticking and wellbore geometry, can be caused by key seats, anomalies in the wellbore geometry, junk in the hole and also problems with cement. How each of these mechanisms further affects the drilling operations, will be explained in greater detail following.

2.1.1 Key seat

When the drilling string is rotated, the drill pipe is under tension due to the weight of the drill collars. If the drilling string passes through a dogleg or a crooked hole, the string will touch the lower side of the bore hole. Continued drilling in this position will gradually wear away a small hole (groove) into the side of the wall. The problem becomes obvious when tripping out is performed; the tool joint or the bottom hole assembly are pulled into key seat and become stuck at the narrow groove.

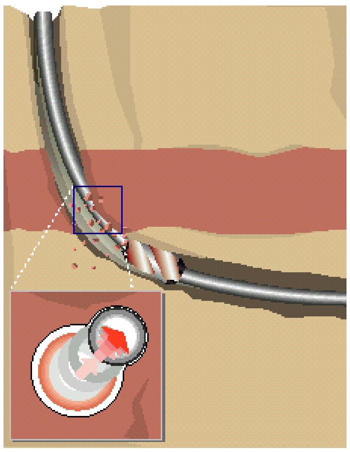

Figure 1 - Key seat - (2)

In deep holes, an estimated 50% of all stuck pipe problems are contributed to or caused by key-seating. [3]

2.1.2 Ledges and doglegs

A dogleg can be defined as a change in the hole angle due to both deviation from the vertical and a change in hole direction. It is expressed either in degrees per 100 feet of course length for the imperial measurement system, or in degrees per 30 meters of course length for the metric system.

Typically, a dogleg is caused by a change in the dip of the formation or by a change in the applied weight on the bit. Severe doglegs can cause drill pipe failure and the inability to run the casing to the planned depth. In a situation when the casing has been successfully run through a dogleg, excessive wear on the production equipment may occur.

Ledges may form where soft and hard formations alternate. (4) They are formed when the tool joint or stabiliser wears away soft and naturally fractured formations, while the hard formations are still in the gauge.

Figure 2 - Dogleg and ledges - (2)

2.1.3 Under gauge hole

If the wellbore is under gauge for any reason, then full gauge tools such as the drill bit or stabilisers may become stuck if moved into the under gauge part of the hole. (5) Very often an under gauge hole is linked with hard and abrasive formations, because the abrasive formation wears down the gauge protection on the bit and stabilisers, and then the hole diameter decreases. If a new bit/BHA is tripped into an under gauge hole, a stuck pipe situation can occur. Additionally, if coring is performed with a smaller diameter of core head than the new bit, it can get stuck at the top of the coring section.

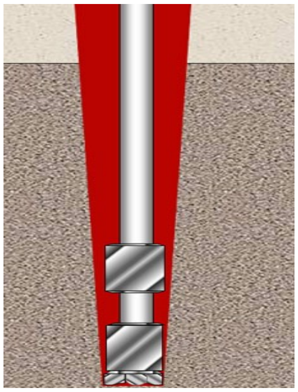

Figure 3 - Under gauge hole - (6)

2.1.4 Junk

Junk can be defined as an undesirable object in the borehole, which is not meant to be there. Keeping in mind that the clearance between the casing and collars or stabiliser is not large, even a small piece of junk can cause a stuck pipe situation. Junk usually either enters the wellbore from the surface due to poor housekeeping on the rig floor or as a result of surface/downhole equipment failure.

Figure 4 - Junk in the borehole - (2)

2.1.5 Collapsed casing

Generally, a collapse occurs when the difference between the internal and external pressure becomes so huge that it exceeds the estimated (designed) collapse pressure of the material.

Casing collapse can occur due to inappropriate casing design or due to casing wear, which can cause a reduction in the casing collapse rating.

When casing is set in the borehole, due to a harsh hole environment, the casing string is susceptible to friction and corrosion; which has as its aim a reduction of the casing wall thickness. If the external formation forces are very high or an inflow pressure test on the already impaired casing is performed, a casing collapse can occur.

Figure 5 - Casing collapse - (2)

2.1.6 Cement blocks

Problems with cement blocks often begin subsequent to performing the leak-off test and further drilling operations, when large sized collars or stabilisers can cause blocks of cement to break loose and fall into the borehole. If there are a lot of cement chunks in the annulus, they can easily create a stuck pipe situation.

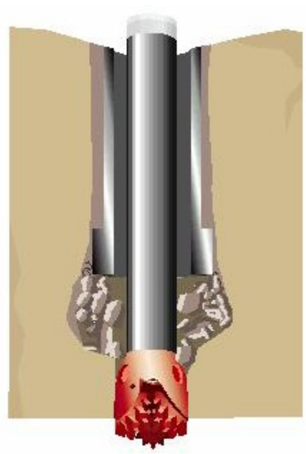

Figure 6 - Cement blocks - (2)

2.1.7 Green cement

A stuck pipe event, due to green or soft cement is not common. It is linked to crew negligence and is related to cement which is not set properly or whose additives have not been chosen correctly in accordance with the borehole environment and the planned operations. After the normal time for Waiting on Cement (WOC), when the drill string is run into the hole to tag the top of the cement, the BHA can pass through cement which is not thick enough, without any weight indicators on the surface. If the running continues, the string can get stuck in the better bonded cement, which has not been contaminated with mud.

Figure 7 - Green cement - (2)

2.2 Differential sticking

Differential-pressure pipe sticking, occurs when a portion of the drill string becomes embedded in thick mud cake and cannot be moved (rotated or reciprocated) along the axis of the wellbore. This happens when a high contact force caused by low pore pressure, high mud hydrostatic pressure, or both, is exerted over a sufficiently large area of the drill string.

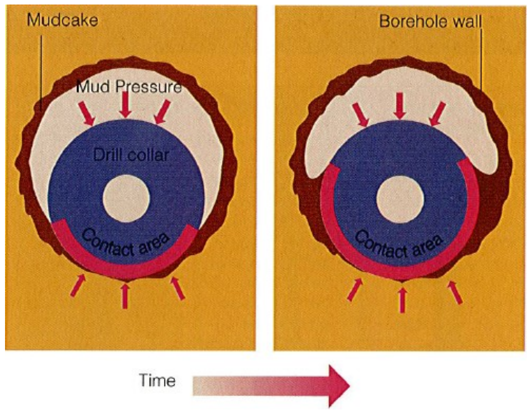

Figure 8 - Cross section of drill collars - (7)

All the aforementioned are presented in the picture above, where the drill collar is embedded in the mud cake due to the differential pressure difference between the mud and the formation. In this situation, the critical factor will be the length of the time interval in which the string will be stationary. As time passes, more mud cake can build up, thus the contact area will increase, simultaneously making the drilling string harder to release.

According to a Chevron survey, based on 600 well histories in the Gulf of Mexico, the probability of differential sticking for a straight hole with water base mud is 20% if the differential pressure never exceeds 2000 psi. (8)

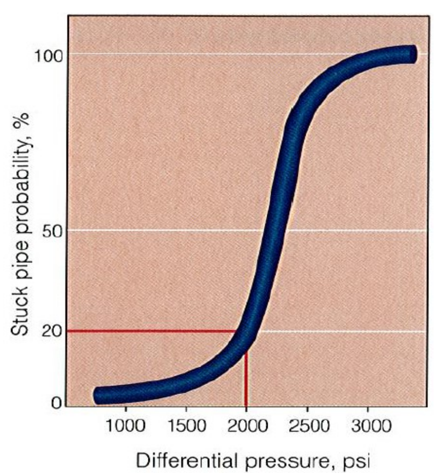

Figure 9 - Probability of differential sticking vs. differential pressure - (8)

In the case of differential sticking, the pull force required in order to free a differentially stuck pipe is:

$$F = (\Delta P)(A)(f)$$

Equation 1

As can be seen from the above equation, the differential sticking force is dependent on the area of contact between the pipe and the mud cake, as well as on the mud weight. [9]

The problem of reducing the impact of differential pressure is very often difficult to manage, due to a long open hole section, where the formation pore pressures are different. For this reason, the mud weight for one layer in the open hole will impose a large pressure differential across another layer of the formation.

2.3 Solid induced pack-off

The term "pack-off" defines the deposition of solid particles (cuttings, cement fragments, etc.) around the drill string, causing wellbore plugging. This can occur due to a variety of reasons, but the most common reasons are due to poor hole cleaning, and/or formation geomechanical rock mobility and instability. [10] When pack-off occurs, circulation is restricted, or it is sometimes impossible to achieve. Also, rotation and axial movement are restricted.

2.3.1 Unconsolidated formation

Unconsolidated formations are composed of loose material, ranging from clay to sand and gravel. Due to their loosely packed nature, with little or no cementing agent, they are unstable. When the mud flows through the spaces between the grains, the collapse of the formation occurs, causing a stuck pipe situation.

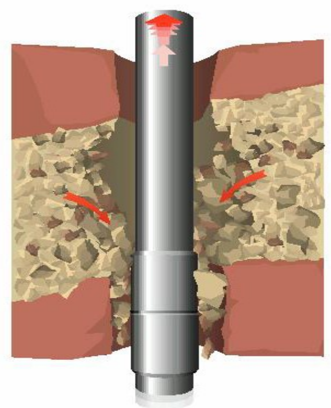

Figure 10 - Unconsolidated formation - (2)

2.3.2 Mobile formation

Due to overburden forces, a mobile formation becomes squeezed into the wellbore. It behaves in a plastic manner, which means that it deforms under pressure. The usual types of formations which cause this phenomenon are shale and salt. Deformation under this type of mechanism can reduce the wellbore diameter and cause problems while running tools.

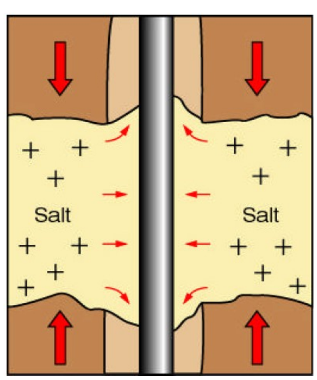

Figure 11 - Mobile formation - (11)

2.3.3 Fracture and fault formation

A natural fracture system in rock can often be found near faults. Rock near faults can be broken into large or small pieces. If the rocks are loose they can fall into the wellbore and jam the string in the hole. Even if the pieces are bonded together, the impact from the BHA, due to drill string vibration, can cause the formation to fall into the wellbore. (12)

Therefore, a stuck pipe situation due to this type of mechanism usually occurs while drilling tectonically active zones and naturally fractured formations such as sandstone, limestone and carbonate.

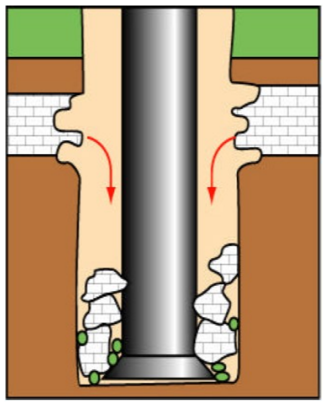

Figure 12 - Fracture and fault formations - (11)

2.3.4 Naturally over-pressured shale collapse

Naturally over-pressured shale has a natural pore pressure greater than the normal hydrostatic pressure gradient. Naturally over-pressured shales are most commonly caused by geological phenomena such as under-compaction, naturally removed overburden and uplift. Using insufficient mud weight in these formations will cause the hole to become unstable and collapse. (2)

Figure 13 - Naturally over-pressured shale collapse - (2)

2.3.5 Induced over-pressured shale collapse

Induced over-pressure shale occurs when the shale assumes the hydrostatic pressure of the wellbore fluids after a number of days exposure to that pressure. [2] The risk of a stuck pipe situation becomes obvious, when pressure reduction into the wellbore occurs and the shale with its trapped pressure becomes unstable and collapses into the wellbore, as it does in the case of naturally over-pressured shale.

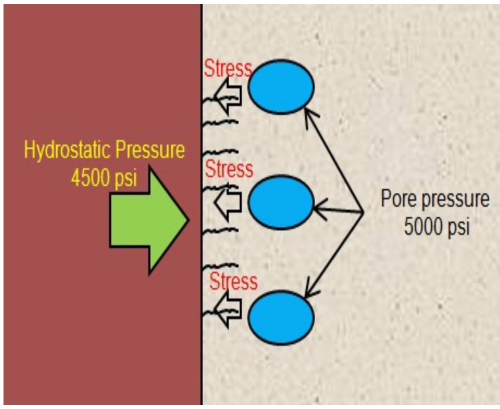

Figure 14 - Induced over-pressured shale collapse - (13)

2.3.6 Reactive formations

Reactive formations are formations which are composed of montmorillonite and bentonitic shales. The clays within the shales absorb water from the mud and fall into or swell in the borehole. During the tripping operations, the drill string can become stuck in the swelled section of the borehole. The problem is more prominent if water based muds are used. The problem of swelling can also occur during drilling with oil based muds if the salinity of the formation is higher than the salinity of the mud.

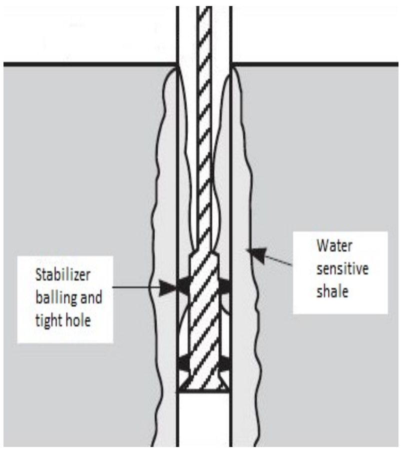

Figure 15 - Reactive formation - (14)

2.3.7 Tectonically stressed formations

Throughout history, the earth's crust has been subjected to the impact of different tectonic, volcanic and sedimentation activities.

Tectonic stresses build up in areas where rock has been compressed or stretched due to the movement of the earth's crust. The rock in these areas is being buckled by the pressure of moving tectonic plates. [2]

When drilling is performed in such areas, the rock around the wellbore will collapse and cave into the borehole. This phenomenon is widespread in or near mountainous areas, where adequate drilling fluid density should be used to stabilise tectonically stressed formations.

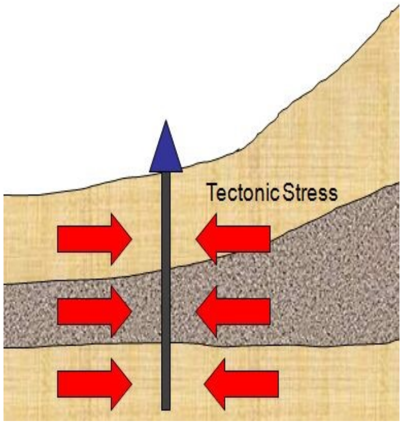

Figure 16 - Tectonically stressed area - (13)

2.3.8 Hole cleaning

The most important factor for an economically drilled wellbore is to achieve good bottom hole cleaning and remove cuttings from the annular space. This can be achieved with the proper selection of drilling fluids, whose purpose is to suspend solid particles and efficiently transport them to the surface. The drilling fluid must also provide borehole stability, cooling and lubrication of the bit, minimise formation damage and provide information about the wellbore. The mud circulation path in a vertical well is depicted below.

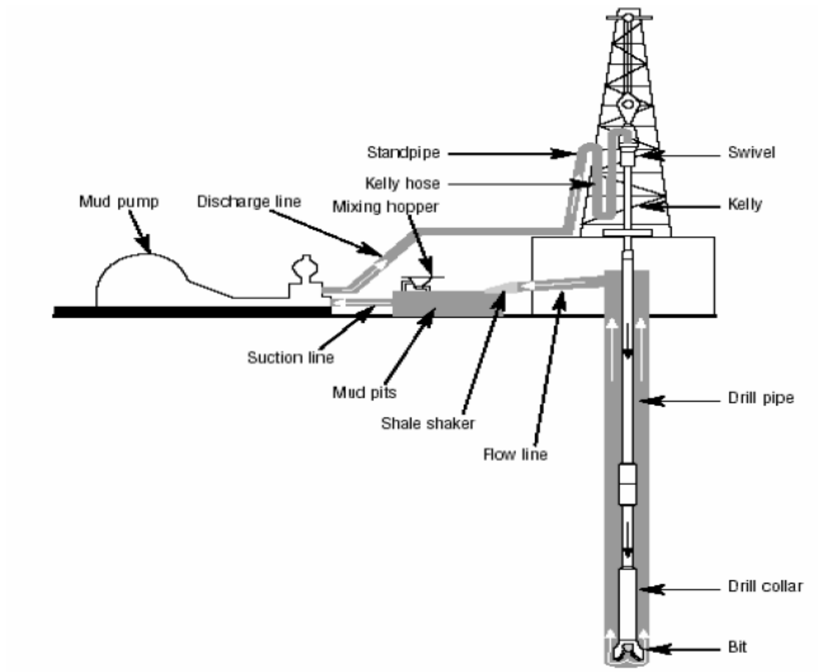

Figure 17 - Mud circulation system - (15)

The ability of the drilling fluid to efficiently transport drilled cuttings to the surface and to provide suitable bottom hole cleaning is subject to the following factors:

- Cutting properties
- Cutting slip velocity
- Annular mud velocity
- Cutting transport
- Drill pipe eccentricity
- Drill pipe rotation
- Proper rheology
- Cuttings' bad properties
- Rate of penetration

In 2000, Rishi B. Adari, Stefan Minsk and Ergun Kuru, came up with the idea of presenting all of the listed factors schematically, in accordance with their influence on hole cleaning. [(16)]

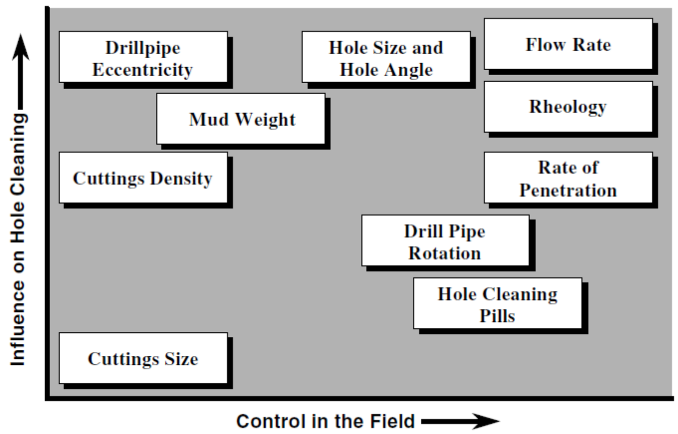

Figure 18 - Key variables controlling cutting transport - (16)

Pipe eccentricity, has a strong influence on cutting transport in the annular, but is mainly an uncontrollable factor, while hydraulic and mud rheology are the most important factors. Rheological properties (mud weight, viscosity, yield point and gel strength) enhance the transport of the cuttings and have an important effect on the overall hydraulics of the system.

2.3.8.1. General factors affecting hole cleaning

There are a lot of different parameters (factors) which influence the hole cleaning process. For some of them the driller has direct control, but others are unpredictable and are specific to the type of formation which will be drilled. The most important will be presented as follows.

Basic physics related to cutting transport (properties)

To repeat the aforementioned, one of the main functions of a drilling fluid is to successfully remove cuttings from the wellbore. From the physical point of view, each cutting particle is determined by its size, shape and density.

The specific gravity of most rocks that are drilled is roughly 2.6, and it is assumed that this is known, but the shape and the size of the cutting is very difficult to predict. According to Azar [17], the shape and size of cuttings are a function of the bit type (drag, roller cone bits), the regrinding process that occurred when the drilled cuttings were generated beneath the bit, bombardment and finally breakage by the drill string rotation.

From a mechanical point of view, two different cutting transport mechanisms were identified. The first one occurs when the cuttings are transported to the surface by a rolling/sliding motion and the other is when the cuttings are in suspension.

A single particle at the cuttings bed surface is subject to several forces:

- Gravity, F_b, and buoyancy, F_b, are static forces due to the properties of the particles and their surrounding fluid
- Drag, F_D, and lift, F_L are hydrodynamic forces incurred from the fluid flow
- Van der Waals forces, F_{van}, are interparticle forces existing between any neighbouring particles [18]

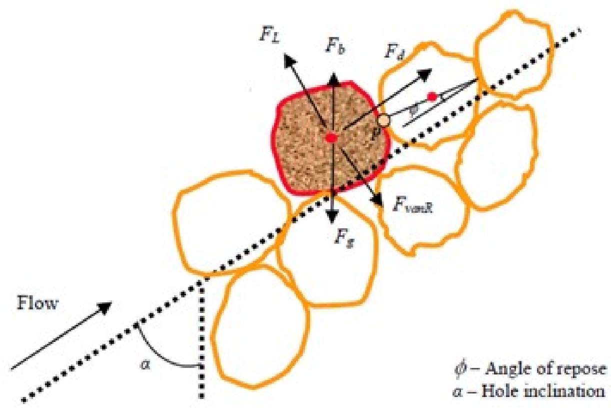

Figure 19 - Forces applied on single cutting particles on the solid bed surface - (18)

In the case of suspension, the situation with forces acting on the drilled particles is a little different. Two groups of forces act on single particles:

- Static ones: the gravity force F_g and the buoyancy force F_b
- Dynamic ones: frictional force, which is decomposed into a drag force F_D (which follows flow direction) and lift force FL (which is perpendicular to the flow movement). The frictional forces depend on the fluid velocity around the cutting particle. [19]

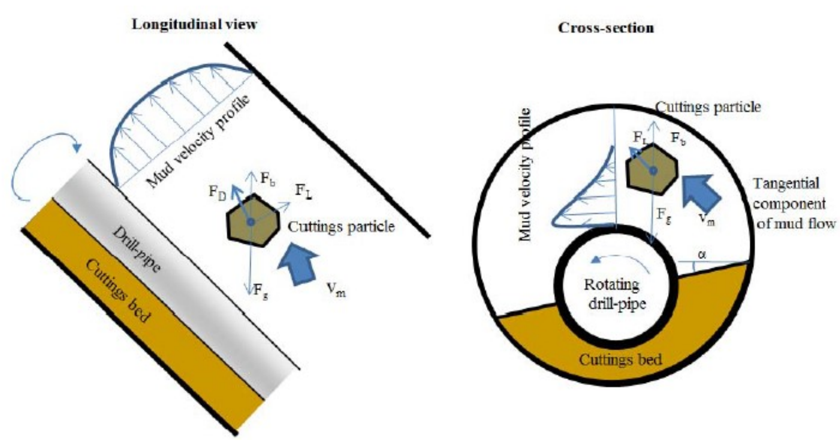

Figure 20 - Force acting on a cuttings particle in suspension - (19)

It is known that fluid velocity is not uniform in the annular cross section. The highest velocity is in the middle of the flow path and around the drill pipes, while the lowest is near the walls and on the low side when the drill pipes are decentred. The particles, which are not in the main fluid stream, will probably settle down and develop a cuttings bed. If the drilling fluid flow is turbulent, the already accumulated particles have a high chance of being lifted and removed from the wellbore. It is also possible to achieve a similar effect with a drilling string rotation, when the particles from the low side of the wellbore are lifted into the main stream. The effect of pipe rotation on the particles will be presented in detail later.

It is also important to mention that solid beds are usually formed in a high angle and in horizontal wells. Smaller cuttings are easier to keep in suspension than larger ones. Furthermore, the amount of smaller generated cuttings, when circulation is stopped, in high angle and horizontal wells, is higher. [20] Moreover, it was observed that a cuttings bed formed from smaller particles is more difficult to erode with viscous fluid than one formed from larger particles. [21]

Determination of cutting slip velocity

The term cutting slip velocity (V_s), defines the rate at which the drilled cutting transported up the hole of the annular falls downward, in the opposite direction to the annular flow. To achieve good annular cleaning, the average annular velocity must be in excess of the average slip velocity. Slip velocity greatly depends on the difference in the densities and velocities of the drilling fluid and on the shape, size and density of the cutting.

Slip velocity for spherical particles in the laminar flow can be determined by the Chen correlation, as follows: [22]

$$v_S = 0.07\left(\frac{\mu_a}{\rho_m \times d_p}\right)\left[\sqrt{\frac{152437 \times d_p}{\left(\frac{\mu_a}{\rho_m \times d_p}\right)^2}\left(\frac{\rho_p - \rho_m}{\rho_m}\right)+1}-1\right]$$

Equation 2

For bentonite suspension in water based mud, Chen proposes using plastic viscosity (PV), as apparent viscosity (μ_a). He also suggests in the case of polymer mud for apparent viscosity, that the following equation be used:

$$\mu_\alpha = PV + 0.03 \cdot \left(\frac{\tau_0 \cdot d_p}{v}\right)$$

Equation 3

For successful cutting transport from the wellbore to the surface, the required minimal and maximal annular velocity must be:

$$V_a(\min) = 1.5 \cdot V_s$$

Equation 4

$$V_a(\max) = 2 \cdot V_s$$

Equation 5

Annular mud velocity

For flow through the annulus around the drill pipes it is assumed that the flow is in a laminar regime due to small annular velocity and low pressure losses, which are required to push the drilling fluid out of the wellbore. For an estimation of the annular velocity, the following equation can be used:

$$v_a = \frac{q}{0.7854(d_2^2 - d_1^2)}$$

Equation 6

Minimal annular velocity depends on the cuttings carrying velocity of the drilling fluid. If annular cleaning is not good, hydrostatic pressure in the annular increases and can cause fluid losses into the formation and stuck pipe conditions.

Hole size mm (inch)	Average ROP m/h	Quantity of rock (2.51 SG)		Drilled mm/min
		dm^3/h	ton/h	
660.4 (26 inch)	1.00	342.0	0.86	0.28
	2.00	684.0	1.72	0.56
	5.00	1710.0	4.29	1.39
	10.00	3420.0	8.58	2.78
	20.00	6840.0	17.16	5.56
444.5 (17 ½ inch)	1.00	155.2	0.39	0.28
	5.00	776.0	1.95	1.39
	10.00	1552.0	3.90	2.78
	30.00	4656.0	11.69	8.34
	60.00	9312.0	23.37	16.68
311.15 (12 ¼ inch)	1.00	76.04	0.19	0.28
	5.00	380.2	0.95	1.39
	10.00	760.4	1.91	2.78
	30.00	2281.2	5.72	8.34
	60.00	4562.4	11.45	16.68
215.9 (8 ½ inch)	1.00	36.6	0.092	0.28
	5.00	183.0	0.46	1.39
	10.00	366.0	0.92	2.78
	30.00	1098.0	2.76	8.34
	60.00	2196.0	5.52	16.68

Table 1 - Cuttings generating rate - (23)

As in Table 1; the cuttings' generating rate shows the amount of generated cuttings which will dictate the minimal value of annular velocity by maintaining the minimal equivalent fluid density below the fracture pressure of the formation.

Furthermore, the minimum annular velocity value is also influenced by the settling of the drilling cuttings (cutting slip velocity). When the slip velocity becomes greater than the annular velocity, cuttings beds will develop as consequence.

According to experimental studies performed by Iyoho [24], higher mud velocity in the annulus improves hole cleaning, regardless of the hole angles, the flow regime and fluid viscosity.

Cutting transport

In vertical wells, it is easier to achieve a good cutting carrying capacity, than in deviated and high angle wells. Due to the impact of gravity force, the drilling string always tends to lie on the lower side of the borehole.

An experimental study performed by Tomren [25] showed that cutting movement and concentrations for bore hole deviations up to 10° in straight-hole drilling, should not pose any special hole cleaning problems. At 10° inclination, the particles will mainly be transported on the low side of the annulus at a low flow rate. As the inclination increases, simultaneously the cutting concentration increases and a higher flow rate is required to obtain the predicted amount of cuttings on the shale shakers.

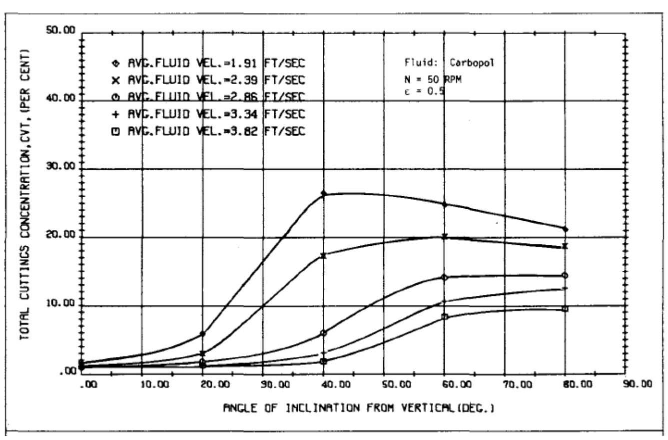

Figure 21 - Variation of cutting concentration with inclination - (25)

The behaviour of the cuttings in the annulus will change gradually if the angle of inclination increases from 10° to 30°, as can be seen in Figure 20, but still, there will be no dramatic change. Due to the increase of radial slip velocity, more and more particles will be pushed toward the lower side of the annulus, which will cause the formation of a cutting bed.

The concentration of the cuttings on the low side of the borehole will increase especially at low flow rates.

Angles between 40° and 50° are the most critical, not only because the cuttings build a bed, the larger problem is the gravity force which tends to slide the bed downward. The problem becomes more pronounced when the circulation stops and the entire volume of the annulus drops like an avalanche, causing an annular pack-off.

For high angles of inclination between 60° and 70°, the formation of the cuttings bed is still present. The mitigating circumstance is that the cuttings bed will not slide downward when the circulation is stopped.

Velocity distribution profile as a result of Eccentricity and Outside/Inside Pipe-Diameter Ratio

On the basis of the equation which was developed by (Iyoho and Azar), [26]

$$v = \frac{n}{n+1} \cdot \left(\frac{\Delta p}{IL}\right)^{\frac{1}{n}} \cdot \left[\left(\frac{h}{2}\right)^{\frac{n+1}{n}} - |y|^{\frac{n+1}{n}}\right]$$

Equation 7

for the velocity profile that occurs in the laminar flow inside an inclined annulus, for the non-Newtonian power law fluids, the following results were obtained:

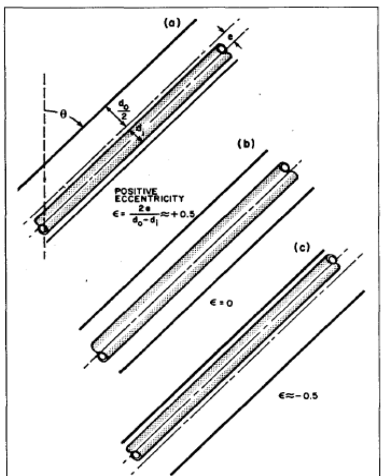

Fig. 3—Definition of annular eccentricity (from Iyoho[2]): (a) ε = +0.5, (b) ε = 0, and (c) ε ≈ −0.5.

Figure 22 - Definition of annular eccentricity - (24)

Displacement of the inside pipe toward the lower wall of the annulus reduces the mud velocity in that area, which is presented in the picture above.

In the case of positive displacement, the situation becomes worse, especially for a higher angle of inclination. If the radial component of the cutting slip velocity increases, the cutting beds will be developed, presently.

Pipe rotation

In rotary drilling technology, the entire drill string is kept under rotation, except during connection or tripping operations. Pipe rotation induces some additional turbulence in flowing mud, which begins to rotate in the direction of the string. The highest velocity of rotational movement is on the pipes' edges, which decreases with distance from the string.

Figure 23 - Pipe rotation helps fluid flow in the narrow side of an eccentric annulus - (27)

According to studies performed by R. Caenn, H. Darley and G. Gray [(28)], the impact of pipe rotation on hole cleaning in a vertical, or near vertical well, is minor.

The string’s rotational movement forces the particles to rotate and then pushes them to the wall side, where lower annular velocity exists. These particles can start to settle, but due to the string’s vibration, which is a product of the rotational motion, the cuttings start to re-enter into the high annular velocity region and are successfully transported to the surface.

The situation is completely different with a deviated or horizontal well, because the cuttings bed is always formed at the low side of the wellbore. In this case the string rotation will initiate the cutting’s motion and move them into a higher flow area, where the flow rate can transport them to outside of the hole. In a horizontal or deviated well, it is very important to keep the pipe moving, as much as possible otherwise the cuttings bed will develop quickly.

Proper rheology

Rheology can be defined as the science of deformation and flow. It refers to the different properties and characteristics of drilling fluid. These properties of the circulation fluid have an effect on the successful removal of cuttings from the wellbore.

The rheology is directly linked to the shear forces whose main purpose is to suspend cuttings and transport them to the surface. Flow rate, flow regime, pipe eccentricity and borehole inclination are the factors which affect the rheological properties of the fluid and finally result in the effective removal and transport of cuttings from the borehole.

It is also worth mentioning, that for a horizontal or near horizontal wellbore, hole cleaning is more efficient if a low viscosity fluid is pumped in a turbulent flow regime rather than a high viscosity fluid in a laminar regime. (29)

On the basis of experimental studies performed on three different fluids – water, HEC and Xanvis polymers – which was carried out by S. Walker and J. Li, the following results were obtained. (29)

Xanvis and HEC polymer-based fluids are more effective than water in terms of solids-carrying capacity, but they cannot erode a stationary cuttings bed as effectively as water can. Moreover, they also experimented with water and Xanvis in a vertical wellbore, where better hole cleaning was achieved with a high viscosity fluid (which was pumped in a laminar regime), than with a low viscosity fluid in a turbulent flow.

Cuttings bed properties

Cuttings bed properties, according to scientific studies performed by S. Walker and J. Li, have a major influence on hole cleaning. (30) In the situation where the bed is loose and porous, it is only necessary to remove single cutting particles which are not adhered to the bed. In this case, there should not be any problem with cuttings bed removal. Otherwise, if the cuttings bed is well consolidated, without free particles which can easily be removed from the bed by flow, hole cleaning will be difficult.

Moreover, they concluded that it is crucially important to minimise cuttings bed consolidation, as much as possible. Also, a small volume of drilling fluids can migrate through a loose and porous cuttings bed, which will simultaneously help to keep the cuttings bed loose.

Rate of Penetration (ROP)

From an economical point of view, higher ROP is always preferable; from another, it can cause a lot of different problems, such as the amount of cuttings in the annulus, larger borehole diameter and low annular velocity. A higher rate of penetration is directly linked to the flow rate. Higher cuttings concentration in the annulus requires flow rates which are able to effectively remove the cuttings from the wellbore and transport them to the surface. Otherwise, the cuttings will settle and can cause excessive torque and drag, mechanical sticking and finally ROP reduction.

2.3.8.2 Rig site monitoring

At a well site many indicators can be used to examine how effective the wellbore cleaning is. Generally, there are the initial signs – if something strange has happened in the wellbore. A good driller will pay attention to all the indicators which are coming from the wellbore and will plan the forward action to be performed. Some of the poor hole cleaning indicators are listed below [(23)]:

a) Rate of removal of cuttings at shakers vs. expected time
b) Size and shape of the cuttings at the shakers (small rounded cuttings indicate the possible process of re-drilling cuttings and the formation of a cuttings bed)
c) Increase of torque and drag (erratic signal on the torque or stand pipe pressure indicator can also be an early warning of cuttings bed development, or can indicate a problem with wellbore geometry and hole cleaning)
d) Poor weight transfer to bit due to wellbore inclination
e) High pick-up weight

3 Freeing a stuck pipe

The most important aspect in a drilling operation is knowing: “What's happening in the wellbore”. Skilled drillers must be able to immediately recognise a problem, according to the current situation and the information available. When the problem is defined – in our case we will investigate a stuck pipe situation – the following step is: “What should be done next?” Each company has its own manual for solving a stuck pipe situation. It’s difficult to say which solution is the best one because each of them is based on lengthy experience and various laboratory and field experiments.

According to D. Abdelung, W. Askew and J. Bernardini [(31)], freeing a stuck pipe involves finding the right combination of gentle persuasion and brute force. The term “gentle persuasion”, refers to a change in the downhole conditions which will result in sticking reduction, so the pipe comes free on its own, or it reacts better to applied force. Under the term “force”, the required strength, which should be applied to help to the string move away from the borehole, is defined.

The force is delivered to the drill string by overpulling the pipe, hanging on, or applying and holding torque. Moreover, a drill jar can also be used if it is run with a drilling string into the wellbore at the proper position in the BHA (depending on the assumption of most likely point at which the pipe will get stuck – on the bottom or upper part of the BHA). Delivering a blow up, down, or in both directions, the string can be released easily.

The tools for persuasion are spotting fluids, hole conditioning and changes in hydrostatic pressure. The spotting fluid is a small volume of mud or a pill, which includes in its composition special mixtures of drilling fluids, whose purpose is to soak the annulus formation, above and below the stuck point, by lubricating and/or breaking the mud cake where the pipe is held by the wellbore.

A diesel pill is the traditional soaking fluid for freeing a stuck pipe. Due to its negative impact on the environment, some companies, with the attempt to follow governmental regulations, have switched to more environmentally friendly mineral oil spotting fluids. The effect of both on the formation is similar, but the level of efficiency is still different. According to the research data of R. C. Ayers jr. and J.E. O´ Reilly, [(32)] based on 528 wells in the Gulf of Mexico, the rate of success in string freeing with diesel fluid was 51%, while for mineral oil pills it was 33%. The spotting fluid should be prepared and pumped as soon as possible, as the chance of freeing a stuck pipe decreases over time.

Changes in the flow rate or mud rheological properties are sometimes the trigger for a stuck pipe situation. The impact on the condition of the wellbore is visible in the case of horizontal or high inclination wells, where a change in the flow rate or mud properties has a direct impact on the formation of the cuttings bed, and simultaneously on the stuck pipe situation.

A change of hydrostatic pressure is always required, however, sometimes the crew is not able to reduce so much mud density due to potential influx (a kick) from the formation occurring.

For solving a stuck pipe situation, "U-tube" can be used as an alternative method for releasing the drill string. This method aims at a reduction of the annular hydrostatic pressure, by pumping lower density mud inside the drill pipe. Due to the "U-tube" effect, higher density mud from the annulus will start flowing into the drill pipe, until equilibrium in the hydrostatic pressure is achieved. This should result in a reduction of the differential pressure and the simultaneous release of the stuck pipe. The other method, which should also provide differential pressure reduction is a drill stem test (DST) tool, which should be installed on a fish, after the back-off procedure has been applied.

The main problem with a stuck pipe situation is that, within a very short time after getting stuck, the situation worsens and if it is not recognised and reacted to quickly, in most cases it will lead to side-tracking or even abandoning a well.

3.1 Key seat as the cause of a stuck pipe situation

Stuck pipe due to key seat can occur only while pulling the drill string out of the hole when the drill collar or stabiliser gets stuck at a specific depth. The risk of key seat increases when a section of high dogleg severity exists and drilling through this dogleg section without a short trip and back reaming for a long time.

At the moment of a stuck pipe situation, the flow rate is unrestricted, overpull is increasing rapidly when the BHA is pulled into the key seat, and tripping back operation is usually possible.

For releasing the stuck pipe string Elf proposes the following [31]:

1. Don't pull up the drill string strongly
2. Try moving the drill string down and simultaneously applying torque
3. Start with jarring down
4. A high lubricating pill should be set
5. If the all of the above doesn't provide a result, the back-off procedure should be applied as closely as possible to the stuck pipe point
6. A drill string with a jar should be run into the borehole
    - The outside diameter of the jar should be small enough to enter into the key seat without problems and establish the connection with the fish

7. The jarring operation should be performed in the next two to three hours. If the drill string is still in the stuck, a lubricant pill should be set again and the jarring operation continued
8. In the situation that differential sticking occurs, the string should be backed-off above the key seat

3.2 Ledges and doglegs as causes of a stuck pipe event

A stuck pipe due to ledges and doglegs can occur either during drilling or tripping operations. Before a stuck pipe event, a change in ROP is observed, as well as changes in mud logging samples with both soft and hard rock debris being found in it. At the moment of the stuck pipe event, erratic overpull or set down is observed, the circulation is unrestricted and the problem is linked to the certain depth interval.

In order to distinguish the particular cause of wellbore problems, such as key seat and ledges, some authors have made hook load analyses where they compare hook load patterns with different curves. When the match exists, the particular problem is defined. (33)

For freeing of the stuck pipe, the following procedure should be performed (34), (35):

1. If the stuck pipe event occurs while moving up, start with jarring down under the maximum trip load. Torque can be applied, but with caution.
2. If the stuck pipe event occurs while moving down, start with jarring up under the maximum trip load. Torque should not be applied
3. When the string becomes free, start with reaming or back-reaming in order to remove the ledges and facilitate the string passing through the dogleg

3.3 Under-gauge hole as the cause of stuck pipe

An under-gauge hole is another reason which can lead to a stuck pipe situation. A stuck pipe can occur only while tripping in the hole. At the moment of the stuck pipe event the circulation is unrestricted or is slightly reduced, the string hangs on and the bit gets stuck off bottom.

When the stuck pipe occurs, the following procedure should be performed (11), (34):

1. Start with jarring up under maximum trip load
    - Jarring down should be avoided, because it will deteriorate the situation
2. If the first procedure doesn't give results, consider the use of an acid bath

3.4 Stuck pipe due to junk

A stuck pipe condition due to junk is rare. The reason for stuck pipe is sometimes easy to assume and expect, but stuck pipe due to downhole equipment failure can happen at any time, without any indications. At the moment of the stuck pipe the circulation is unrestricted, but torque and drag suddenly increases.

For freeing the stuck pipe, Elf proposes the next procedure (31):

1. With the mud pump, try to vibrate the pipe while moving in the opposite direction from that prior to the stuck pipe situation
2. Start with jarring down
3. A lubricant pill should be set and then continue with the jarring operation until the string is freed

In the case of a stuck pipe situation, the BP suggests the following steps (31):

1. Start working the string and applying a jarring operation in both directions
2. Forces should be increased gradually
3. Continue working the string and jarring, but only upward
4. Maximum jarring forces should be applied from the beginning

For freeing a stuck pipe, the following procedure has also been proposed (34), (35):

1. If the stuck pipe situation has occurred while moving up, start with jarring down under the maximum trip load. Torque should be also applied, but with caution
2. If the stuck pipe situation occurred while moving down, start with jarring up. Torque should not be applied

3.5 Casing or tubing collapse leading to a stuck pipe event

The warning signs of casing or tubing collapse are a hang on or overpull while tripping with bottom hole assembly. The casing collapse should also be visible in the calliper log, where its irregular shape and change of inside diameter is observed.

If a stuck pipe event occurs, the crew should perform jarring out of the hole operation, if possible. Otherwise, the back off procedure should be applied as deep as possible and the wellbore should be prepared for side-tracking.

3.6 Cement blocks as the cause of a stuck pipe event

Stuck pipe due to cement blocks can occur anytime during tripping or drilling operations. Before the stuck pipe event, cement fragments are visible at the shale shakers and fine particles can be observed by the geologist on the mud loggers' screens. The torque and drag becomes erratic and at the moment of the stuck, drastically increases. Circulation is unrestricted.

At the moment of the stuck pipe situation, Schlumberger recommends the following (2):

1. Try to maintain circulation
2. If the stuck pipe event occurred while moving up, torque in combination with jarring down should be applied
3. If the stuck pipe event occurred while moving down, the jarring operation should be performed. Torque should not be applied
4. The first hour of jarring should be performed with light loading of up to 25 tonnes and after that, the jarring forces can gradually be increased
5. Circulation should be reduced or stopped, when:
    - The drill string is pulling up, which is necessary in order to accumulate energy for jarring up and hanging on to accumulate energy for jarring down
    - Full circulation is desirable, because it will increase the jarring blows, while jarring up
6. If the above procedure does not provide results, the setting of an acid pill should be taken into consideration

3.7 Green (soft) cement as the cause of a stuck pipe event

A stuck pipe situation due to green cement usually occurs while running the drill string into the hole to dress off the top of the cement. At the moment of the stuck pipe, the pump pressure increases very quickly, the torque also suddenly increases and at very high pump pressure circulation cannot be established.

For freeing of the stuck pipe, the following procedure should be performed (11), (35):

1. Before performing any operation, trapped pressure inside the drill string should be bled off
2. If the stuck pipe event happened while moving up, a jarring down operation should be performed
3. If the stuck pipe event occurred while moving down, a jarring up should be applied
4. Try to establish circulation at all times

3.8 Differential sticking as the cause of a stuck pipe situation

A stuck pipe due to differential sticking occurs when the drill string is in a stationary condition or is moving very slowly. It can also take place when a high overbalance between hydrostatic and pore pressure exists. Prior to the stuck pipe condition, the torque and overpull increases while tripping or making a connection. One indicator which clearly specifies that a problem with differential sticking exists is a reduction in the overpull, after performing the reaming operation. In the case of a stuck pipe, the drill string cannot be moved and rotated, but mud can be circulated without restriction.

In the situation that differential pressure is the cause of the stuck pipe, Elf recommends the following procedures [(31)]:

1. Shut down the mud pumps or reduce the pump output in order to reduce effective mud density at the stuck pipe point
2. Try to pull the drill string with the maximum possible force
3. Apply proper force to activate the jar and start with jarring under maximum permitted force
4. If the bit is off bottom, start with jarring upward for approximately one hour; after that start with blows in both directions
5. Between two blows the torque should be periodically applied
6. If all the above-mentioned actions do not give the expected result, the crew should perform stuck pipe point determination by stretching the drill string (using Driller's method)
7. After the stuck pipe point is determined, a surfactant pill should be prepared and set as soon as possible
8. If the stuck pipe situation still exists and there is no risk of formation fluid inflow, the crew should perform the following procedure:
    - The back-off procedure should be performed as deeply as possible
    - The DST tool should be run into the hole and connected with the fish. The tester valve should be open for a short-time (approximately one minute), in order to permit formation fluids inflow into the wellbore and it should relieve differential pressure on the formation

Compared to the Elf recommendations, BP assumes that the circulation during differential sticking is almost normal and does not recommend switching off or reducing the pump rate.

BP suggests the following in order to release a stuck pipe string [(31)]:

1. Start working the drilling string immediately.
    - In the case that the bit is off bottom, slump the pipe under the right-hand torque and hold it
    - In the case that the bit is on the bottom, the string should be pulled under maximum force and periodic jarring should be started
2. Apply right hand torque in an attempt to create movement at the stuck point
3. After a certain time, if the above listed attempts fail, start working the string in both directions
4. Hydrostatic pressure reduction should be the next step. Before performing hydrostatic pressure reduction, the crew must take into consideration all aspects of well control
    - It is known that pressure reduction is most successful if the drill string is under compression
5. If the drill string is still in the stuck pipe condition, free point determination should be performed
6. Prepare a pill with sufficient volume and with a density 0.02 S.G. heavier than the actual mud used
7. Put the string into compression with slack off 4.5 tonnes below the weight of the free pipe, right-hand torque should also be applied at the value of a half a turn per each 300 m (1000 ft) of pipe above the determined stuck pipe point
8. After every 5 minutes the torque should be released and the string will be pulled up with 4.5 tonnes
9. An additional volume of the pill should be kept in the drill pipe and after each 30 minutes 80 litres should be slowly pumped in order to move more pill into the borehole
    - Working the pipe up and down should be continued
    - The formation soaking time should be more than 12 hours, but not longer than 40 hours
10. If the all the above-mentioned actions do not provide a result, the "U-tube" method should be applied. For a performing this method, there should be no fluid formation inflow

In the case of stuck pipe, Eni states that the following steps should be taken [36]:

1. Immediately start working the pipe up and down in combination with right-hand torque
    - The maximum torque value should be determined in order to avoid twist off of the drill pipe due to biaxial load
2. Prepare and spot a releasing pill (crude oil, oil containing surfactants if permitted, otherwise use mineral oil) around the BHA at the stuck pipe zone
3. If the wellbore is stable and there is no risk of any inflow, the mud density should be reduced gradually

4. Operations with a drilling jar, or bumper sub should be performed
5. Performing a DST procedure, if the previous operations don't provide results

For freeing the stuck pipe string, Schlumberger proposes the following procedure [2]:

1. At the beginning, circulate with the maximum possible flow rate to erode the filter cake
2. Release the drawworks brake to allow the top pipe joint to slide down while holding 50% of the torque used for making-up the tool joint. Do not apply torque when the tapper drill pipe string is in use
3. Pick up slightly above the drill string weight and perform the first step again
4. After a certain length of time, the first and second step should be repeated, with increasing torque to a value which corresponds to that of the drill pipe make up torque
5. If the drill string is still in a stuck pipe condition, a pill should be prepared and the spot or "U-tube" method should be performed

3.9 Stuck pipe due to unconsolidated formation

A stuck pipe due to unconsolidated formation can take place either while tripping or drilling through loose formations which can flow into the wellbore. During drilling operations, a small volume of mud is constantly lost, while the mud weight increases. The volume of unconsolidated formation fragments such as sand, gravel, pea on the shale shaker increases.

At the moment of the stuck, the pump pressure and torque suddenly increase. While picking up the string, abnormal drag is observed. The circulation is restricted or it is impossible to achieve.

In the case of a stuck pipe situation in unconsolidated formations, Schlumberger suggests [2]:

1. At the first sign of erratic torque and overpull during drilling through unstable formations, which can cause the drilling string pack-off, the pump rate should be reduced by 50%
    - With reduction of circulation capacity, the value of the trapped pressure below the pack-off section, will be minimised
    - If a higher pressure is applied on the pack-off section, the situation will deteriorate
    - If the reduced circulation capacity cleans up the hole, flow rate should return to the normal rate
2. If the first step fails and a drill string is packed-off, the pumps should be switched off and the stand pipe pressure, bled down
    - The stand pipe pressure should be bled down under a controlled rate, otherwise formation debris can get in and plug the drill string
3. A low pressure (less than 35 bar) should be kept trapped below the pack-off

- If the pressure is bled-off, this can be an indicator as the situation improves

4. A maximum of 35 bar pressure should be held inside the drill pipe, with the weight of the drill string which is equivalent to the string weight before stuck pipe, under the tension and torsion
    - At the same time start with drill string cycling up to the maximum make-up tool joint torque
    - Working the string up or down is not recommended yet
5. Start with applying torque, occasionally. Bleed-off trapped pressure and monitor the return flow at the surface
    - If bleed-off occurs or partial circulation is established, the pump rate should be slowly increased and maintained to the maximum of 35 bar stand pipe pressure
    - The pump rate should be increased if the circulation improves
6. If the circulation cannot be established, working the pipe between free up and free down weight should be performed
    - It is imperative to avoid excessive pulls and set down weight (max 25 tonnes), in order to avoid worsening the situation
    - While periodically working the string, the torque should be also applied. The stand pipe pressure should be kept at the constant value of 35 bar
7. The usage of jars or bumpers should be absolutely avoided
8. If circulation has not been established yet, stand pipe pressure should be increased gradually up to 103 bar, working the string in combination with applying torque should be continued
9. When full circulation is established and the string is still in the stuck condition, start working with the jar, but in the opposite direction of the last pipe movement
10. If the string is finally released and rotation is established, hole cleaning should be continued, until the tripping operation is performed

For freeing a stuck pipe "Drilling Formulas", suggests the following [(13)]:

1. Try to circulate with low pressure (20-25 bar). A higher pump rate should be avoided, because this will cause more cutting accumulation around the drilling string and will further complicate operations for freeing the stuck string
2. If stuck pipe has occurred while drilling or tripping out of the hole, the maximum allowable torque in combination with jarring down should be applied
3. In the situation that stuck pipe has happened while running in the hole, jarring up with maximum trip load should be applied, without torque
4. If all the above-mentioned result in freeing the stuck pipe, the wellbore should be circulated in order to remove the caved material, before further drilling operations are performed

3.10 Fracture and fault formation as the cause of stuck pipe

A stuck pipe event due to fractured and faulted formation often happens while drilling, but it is also possible during tripping. While tripping, the drill string always touches the side of the wellbore wall and can cause the caving of naturally broken formation material into the borehole. Prior to a stuck pipe situation while drilling, the torque and drag becomes erratic and overpull is also noticed. Huge quantities of large and irregular rock fragment materials with sharp edges may be delivered onto the shakers. At the moment of stuck pipe, the torque and drag suddenly increase. Circulation can be restricted, or exists without return flow.

In order to release the stuck pipe string, the following procedure should be conducted [(11), (35)]:

1. If stuck pipe has happened while moving the drilling string up, apply jarring down with maximum allowable trip load. The torque should not be applied
2. If the drill string is stuck during moving down, start jarring up in an attempt to break the formation debris. The torque should not be applied
3. Circulation should be maintained constantly. High density viscous pills should be pumped into the wellbore in order to transport formation debris to the surface. In the case that the formation is limestone, acid should be used as a spot fluid.

3.11 Mobile formation as the cause of stuck pipe

A stuck pipe in a mobile formation can occur at any time during drilling or tripping operations.

In the situation that the drill string is in a stuck pipe condition due to the existence of salt formation, the torque and ROP may suddenly increase. Also, overpull can be observed while pulling off bottom. There should not be drilled cuttings material on the shale shakers.

At the moment of the stuck pipe event the Elf recommends [(31)]:

1. If there is no circulation, the backing off procedure should be applied as deeply as possible and also all attempts should be performed in order to establish circulation
2. A freshwater pill with dissolved salt in the concentration of 350 kg per 1 m^3 should be prepared and pumped into the wellbore
    - The salt saturated mud should prevent further formation salt dissolving and in this way will prevent creating salt blocks that can fall into the wellbore simultaneously

Alternatively, BP proposes the following procedure [31]:

1. Prepare and pump a fresh water pill into the string
   - The purpose of the fresh water pill is to dissolve the salt at the stuck point which is usually in the BHA
   - Prepare enough volume of the pill to cover the whole BHA and an additional 3 m^3 should be left in the string for reserve
2. Hold the maximum value of the overpull during spotting the fresh water pill
3. In the case that oil based mud has been used, an unweighted spacer which is a combination of water and detergent should be placed ahead of the fresh water pill
4. After two hours, if the fresh water pill has not given any results a second pill should be spotted
5. At all times, the parameters of the well control must be monitored

Another case of mobile formation is plastic shale layers. While drilling out this formation, the torque starts increasing, when picking up the overpull is observed and mud pump pressure increases. In the mud solid content increases simultaneously, changing the mud rheology while the volume of drilled cuttings is less than expected.

In the case that a stuck pipe event occurs, the Elf recommends [31]:

1. If there is no circulation, try to obtain it under maximum pump pressure
2. Pressure up the annulus in order to return the shale back into the borehole wall
3. Start with jarring operations
4. If the drill string is still in the stuck, back-off procedure should be performed as deeply as possible and then continue with mud treatment, with the aim of controlling solid content and mud rheology
5. When proper downhole conditions are established, the borehole should be cased as soon as possible

For freeing a stuck pipe due to mobile formation (regardless of the salt or shale mechanism), some companies perform the same procedure at the beginning. If this doesn't give any results a further procedure will be chosen according to the type of mobile formation (salt or shale) which exists. The procedure is as follows [34], [35]:

1. If the stuck pipe situation has occurred during POOH, torque should be applied in combination with jarring down under maximum trip load
2. If the stuck pipe situation has occurred while RIH, apply jarring up under maximum trip load. The torque should not be applied
3. If there is evidence that the plastic formation is salt and the wellbore is gas kick free, fresh water as a spotting fluid can be used

3.12 Reactive formations causing a stuck pipe situation

During drilling through these types of formations, a stuck pipe situation cannot be excluded. Prior to the stuck pipe condition, increased torque and drag may be observed. Also, overpull may be observed when pulling out of the hole, or off bottom. A change in the mud properties (yield point and plastic viscosity) may exist. A huge amount of hydrated caved material may be delivered to the shale shakers, when the ROP is increased.
At the moment of the stuck pipe situation, high pump pressure at a small pump rate should be observed, and also circulation is restricted or impossible.

For freeing stuck pipe, Elf recommends the following steps [31]:

1. Try to maintain circulation during the entire time that the drill string is in the stuck condition
2. Start with pumping high viscosity and low filtrate mud
3. For the purpose of wellbore cleaning, it is recommended to pump several high viscosity plugs
4. While performing cleaning operations, start working slowly with the drill string
5. If all of the above does not give a result, a high viscosity pill should be set and a back off operations should be performed as deeply as possible
6. The string with a jar and safety joint should be run into the hole and connected with a fish, and jarring should be commenced until the string becomes free

For releasing the drill string BP proposes the following procedure [31]:

1. The focus is on establishing full circulation and on working the string downward
2. Try to establish rotation; the rotation may help in disturbing the pack-off material around the drill string
3. Freeing forces should be slowly increased to the maximum
4. In the case that circulation is obtained, mud weight should be slightly increased in order to prevent possible problems with reactive formation

3.13 Naturally over-pressured shale collapse

Formations whose natural pore pressure is greater than the hydrostatic pressure can also be one of the factors on the list of the most frequent causes of stuck pipe. This stuck pipe mechanism is characterised by increased torque, drag and ROP. Change in the D-exponent can be also observed. A huge amount of large (in size), brittle and concave shaped caved material may be delivered on the shale shakers.

If a stuck pipe situation occurs, the same procedure such as that in the unconsolidated formation can be applied for releasing the drill string.

3.14 Induced over-pressured shale collapse

A stuck pipe due to induced over-pressured shale formations can happen either while drilling or tripping through shale formations. The first sign which indicates a problem with induced over-pressured shale formation is an increase in the rate of penetration (ROP), torque, drag and pump pressure. Shale fragments should be visible on the shale shakers, without signs of hydration. Change in D-exponent should be also observed.

At the moment of stuck pipe, the following procedure should be performed [(11), (34)]:

1. Pump rate should be reduced and circulation should be continued with low pressure (20-25 bar)
    - High pump pressure should be avoided, because it can pack harder accumulated formation material (bridged annulus) and later operations for freeing stuck pipe will become more difficult
2. If drilling or POOH is performed, the maximum allowable torque should be applied in combination with jarring down under maximum trip load
3. If the stuck pipe situation has occurred while RIH, jarring up under a maximum trip load should be performed. The torque should not be applied
4. These actions should be continued until the stuck string becomes free; then continued with a circulation whose purpose is to clean up the wellbore prior further drilling operations

3.15 Tectonically stressed formations

Stuck pipe due to a tectonically stressed formation can occur either while drilling or tripping operations. It usually happens with a well located near a mountainous area.

The first signs on the surface indicating the existence of this type of stuck pipe mechanism are: erratic torque and abnormal drag and fractured pieces of formation being observed on the shakers.

When the stuck pipe situation occurs, it is assumed that the hole is completely packed-off and bridges may be formed. The circulation is restricted, or is very difficult to establish.

In an attempt to free the stuck pipe, the following procedure should be performed [(34), (35)]:

1. Try to circulate with a low pressure, between 20 and 25 bar
    - High circulation capacity should not be applied, because this will cause more cutting accumulation around the drill string and further operations will complicated

2. If the stuck pipe event happens during drilling or POOH, maximum allowable torque should be applied in combination with jarring down under maximum trip load
3. If it happens during RIH, jarring up under maximum trip load should be started and torque should not be applied
4. All of the above should be performed until the string is freed, then the wellbore should be circulated to remove drilled and formation debris

3.16 Poor hole cleaning as the cause of a stuck pipe situation

Inadequate hole cleaning is one of the main reasons for a stuck pipe situation. Cutting properties, slip and annular velocity, cutting transport, pipe rotation and eccentricity, rate of penetration, mud density and rheology are all factors that influence hole cleaning and have been explained in detail in the previous chapter. Prior to a stuck pipe situation, the following indicators can be observed on the surface: the torque and pump pressure becomes erratic and increases; excessive overpull while making connections and during trips exists; also, the overpull reduces during pumping. Moreover, a high rate of penetration is observed, poor weight is transferred to the bit, the tool face is difficult to orientate and return flow is restricted, or is absent. A stuck pipe condition will happen not long after the pumps have been switched off. Circulation is lost and it is very difficult to regain it again.

If poor hole cleaning is the cause of the stuck pipe condition, BP proposes [31]:

1. Obtaining circulation is a priority
2. Working the string downward and simultaneously and gradually applying force
3. If circulation is obtained, try to disturb the cuttings or caved formation material
    - in low-angle holes, high density and viscosity pills should be applied
    - in high-angle holes, low viscosity pills should be applied to disturb cutting beds and effectively remove material from the borehole
4. The circulation should be maintained and rotating with a string in order to further disturb the cuttings should be attempted

4 Analytical model for deriving general freeing procedures

In the previous chapters, each stuck pipe mechanism was explained individually, as well as the changes in the operational parameters which occurred before and at the moment of the stuck pipe event. The success of the freeing procedure is tightly linked with the appropriate determination of the particular mechanism which caused the stuck pipe condition.

When the mechanism has been determined, the next step is the utilisation of the appropriate procedure for releasing the drill string. While searching for stuck pipe freeing procedures, it was observed that each company had its own recommendations for releasing the drill string. When viewed in detail, the only difference that existed was in the sequence of the operations to be applied. Moreover, the same procedure should be applied on a few different stuck pipe mechanisms, which are also sometimes very different. The most important thing is that each of the procedures guarantees some degree of success; or otherwise they would not be included in the company's project documentation.

It is known that time is a very crucial factor regarding the freeing of a drill string and mistakes often occur. So, the author decided to find the appropriate way of linking similar procedures together providing a unique solution, as much as possible, for different stuck pipe mechanisms, while also not reducing the effectiveness of the procedures used.

If the starting point is determined with the three main types of stuck pipe mechanisms:

- mechanical sticking and wellbore geometry
- differential sticking
- solid induced pack-off

the sequences of this research study will continue as follows:

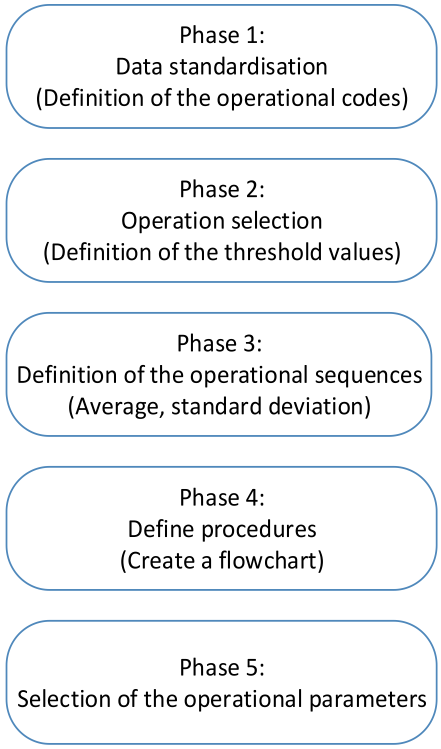

Figure 24 - Workflow

4.1 Analytical model

As stated above, the starting point was determined by the three main types of stuck pipe mechanisms, with further research study to be performed in the manner indicated by the workflow. In order to undertake precise analysis, it is very important that each of the phases is defined with a brief introduction, before the model can become relevant for the purpose of obtaining general freeing procedures for the three main types of stuck pipe mechanisms.

4.1.1 Data standardisation

In each scientific discipline, it is very important to collate, classify and organise data in the appropriate manner, in order to draw conclusions on the basis of applied calculations and comparative values. For that purpose, descriptive statistics offer the possibility to prove any logical uncertainties in a way that can be considered acceptable and useful.

At the beginning of this research the freeing procedures used by different companies were collated. The next actions involved appropriate organisation using a classification model – in this case a coding system. It is important that the contents of each operation within the procedure itself are not changed, otherwise it will become useless.

In terms of the first phase, the companies' procedures (which are composed of the sequences of the different operations) should be coded. The code refers to the shortened description, as well as the unified classification of similar operations, where the meaning of the operation is still retained.

On the basis of the procedures available, a list of the coding system for each operation was developed as the following.

Work string up and down
Circulation
Reduce circulation
Stop circulation
RIH
POOH
Jarring up
Jarring down
Jarring (both)
Torque
Free point determination
Well control
Conditioning
Pump pill
Install equipment
Back-off
DST
Wash-over
Side-tracking

Table 2 - Coding system

4.1.2 Estimation of the threshold values

In order to include an operation in the generalised procedure, a decision was made to include those operations that are most frequent within the companies' freeing procedures that were collated.

Depending on the operation repetitions a threshold value will be derived, below which all results will be discarded. It is always preferable for there to be more than one procedure, as the quality of the developed procedure will increase.

4.1.3 Estimation of the average and standard deviation values

Once a set of operations which fall above the defined threshold value are derived, one should define an algorithm for the operational sequences within the procedure. For this purpose, each code-operation will be given a numerical value which corresponds to the position of the operation within the company's procedure.

For each code, the average sequence value must be calculated. The final procedure should start with operations with the smallest average and continue with the next highest average value.

In the case of two or more procedures having the same calculated average value, the function of standard deviation should be introduced. Those with the lowest standard deviation value get a higher priority in the operational sequence.

4.1.4 General procedure for the three main types of stuck pipe mechanisms

The main goal of this thesis is to end up with a general procedure for all cases of stuck pipe. However, since the mechanisms are quite unique, this is difficult to achieve. The author has agreed with the compromise of developing stuck pipe freeing procedures as per the main stuck pipe mechanism, namely: mechanical sticking and wellbore geometry, differential sticking and solid induced pack-off.

In order to be statistically correct, one should consider performing sub-analysis within the stuck pipe mechanisms. In some cases, this is required because there are very unique sub categories which differ completely from the rest. In other cases, where several procedures are available for a certain stuck pipe mechanism, the author needs to combine them into one procedure in order to avoid wrongly weighted statistical results.

4.1.5 Operational parameters

The last phase of the analysis should provide the meaning of the codes which are included in the general procedure. Therefore, for the purpose of practical usage the general procedure should be transformed into real drilling instructions which can be performed by the driller.

4.2 Application of a statistical model on the main mechanisms

In order to find the appropriate solution for releasing the stuck pipe string, 26 different freeing procedures were collected and analysed. After this the author came up with the idea of trying to develop a model which would assist with the appropriate organisation and combination of these procedures. The segments of the model were clearly presented before in order to derive general stuck pipe freeing procedures for the three main types of stuck pipe mechanisms, such as mechanical sticking and wellbore geometry, differential sticking and solid induced pack-off.

4.2.1 Mechanical sticking and wellbore geometry

Mechanical sticking and wellbore geometry are the first mechanisms within the (already mentioned) group of the three main types of stuck pipe mechanisms and simultaneously it is the starting point for further analysis. On the basis of all the collated freeing procedures for companies, the already developed analytical model should be applied in order to obtain a general procedure for all stuck pipe mechanisms which belong to the group of mechanical sticking and wellbore geometry.

Prior to the analysis being conducted, a coding system should be introduced. Each operation within the collated freeing procedures used by companies should be replaced with a particular code for the purpose of further analysis such as the following:

Mechanical sticking and wellbore geometry								
Key seat	Ledges and doglegs	Under-gauge hole	Junk			Casing or tubing collapse	Cement blocks	Green (soft) cement
Elf	Other sources	Other sources	Elf	BP	Other sources	General recommendation	Schlumberger	Other sources
Work string up and down	Jarring down	Jarring up	Work string up and down	Jarring (both)	Jarring down	Jarring up	Circulation	Well control
Torque	Torque	Pump pill	Jarring down	Work string up and down	Torque		Jarring down	Jarring down
Jarring down	Jarring up		Pump pill	Jarring up	Jarring up		Torque	Jarring up
Pump pill	Conditioning		Jarring down				Jarring up	Circulation
Install equipment							Reduce circulation	
Jarring (both)							Pump pill	

** Other sources - under this term the collated stuck pipe freeing procedures from other sources is defined (Sugar land, Drilling formulas, Stuck pipe prevention)*

Table 3 - Mechanical sticking and wellbore geometry procedures

Frequently one stuck pipe mechanism has more than one different freeing procedure. The idea was to reduce this to just one for each stuck pipe mechanism, for the purpose of obtaining statistically correct values.

From the table, it can be seen that this situation existed in only one case; namely junk in the hole, where three different procedures should be merged into one.

For determination of a unique junk freeing procedure, the first step should be the estimation of the threshold value below which all results will be discarded.

Operations	**Number of repetitions**	**Percentage values**
Work string up and down	2	20%
Jarring down	3	30%
Jarring up	2	20%
Jarring (both)	1	10%
Torque	1	10%
Pump pill	1	10%
SUM	10	100%

Table 4 - Estimation of the threshold values

The threshold value is derived individually for each stuck pipe mechanism, depending on the number of available procedures. It is always preferable for there to be more than one procedure, as the quality of the developed procedure will increase.

In this case, each operation which has a percentage value of more than 10 is taken into consideration for further analysis.

The next step should be the estimation of the average value based on the grading system. This means that each code-operation will be given a numerical value based on its operational sequence within the procedure.

Junk					
Elf	Company's operational sequence	BP	Company's operational sequence	Other sources	Company's operational sequence
Work string up and down	1	Jarring (both)	1	Jarring down	1
Jarring down	2	Work string up and down	2	Torque	2
Pump pill	3	Jarring up	3	Jarring up	3
Jarring down	4				

** Other sources - under this term the collated stuck pipe freeing procedures from other sources is defined (Sugar land, Drilling formulas, Stuck pipe prevention)*

Table 5 - Introduction of the grading system

Operation	Operational sequences			Average values
Work string up and down	1	2		1.50
Jarring down	2	1	4	2.33
Jarring up	3	3		3
Jarring (Both)	1			1
Torque	2			2
Pump pill	3			3

** Red highlighting denotes eliminated operations*

Table 6 - Estimation of the average values

Just as the threshold value was determined in the previous step, the unique junk freeing procedure starts from the smallest to the highest obtained value based on the average value.

Junk-freeing procedure
Work string up and down
Jarring down
Jarring up

Table 7 - Junk-freeing procedure

For performing further analyses, it is very important that each stuck pipe mechanism is defined by its own unique procedure. If there was not a unique procedure for each, the same steps, such as in the case of the junk, should be performed again. After that it should be continued using a known grading system.

Mechanical sticking and wellbore geometry															
Key seat	Company's operational sequence	Ledges and doglegs	Company's operational sequence	Under-gauge hole	Company's operational sequence	Junk	Company's operational sequence	Casing or Tubing collapse	Company's operational sequence	Cement blocks	Company's operational sequence	Green (soft) cement	Company's operational sequence
Work string up and down	1	Jarring down	1	Jarring up	1	Work string up and down	1	Jarring up	1	Circulation	1	Well control	1
Torque	2	Torque	2	Pump pill	2	Jarring down	2			Jarring down	2	Jarring down	2
Jarring down	3	Jarring up	3			Jarring up	3			Torque	3	Jarring up	3
Pump pill	4	Conditioning	4							Jarring up	4	Circulation	4
Install equipment	5									Reduce circulation	5		
Jarring (both)	6									Pump pill	6		

Table 8 - Mechanical sticking and wellbore geometry procedures with a grading system

Before performing further analyses, (which have as their aim obtaining a general freeing procedure for all of the stuck pipe mechanisms within the group of the mechanical sticking and wellbore geometry), an overview on the freeing procedures of a stuck pipe should be undertaken.

The aim of the overview is to separate each of the stuck pipe mechanisms from the mechanical sticking and wellbore geometry group, whose freeing procedures deviate from the others. Otherwise the statistic results obtained will not be correct and the subsequent general freeing procedures that are being strived for may not be applied on some of them.

The deviation in the freeing procedures between the stuck pipe mechanisms is evident in the above table in the cases of stuck pipe due to under-gauge hole and casing or tubing collapse.

At the very beginning when the stuck pipe occurs, performing the operation ˝jarring down˝, instead of ˝jarring up˝ on the first mentioned stuck pipe mechanism, will probably create a very complicated situation, simultaneously reducing the possibility of subsequent release of the drill string. Moreover, the second mechanism also included, after some time, an operation "pump pill˝. If the assumption is made that the pump pill, in the case of the stuck pipe due to casing or tubing collapse (i.e. the second mechanism), will not deteriorate the stuck pipe situation further, except for a delay in time while the remedial action is performed, the following procedure is obtained.

Under-gauge hole and casing or tubing collapse
Jarring up
Pump pill

Table 9 - Under-gauge hole and casing or tubing collapse-freeing procedure

When each of the stuck pipe mechanisms is defined with a unique freeing procedure and all of the procedures have been analysed, the threshold value should be determined.

Operations	Number of repetitions	Percentage values
Jarring up	4	17.4%
Jarring down	5	21.7%
Pump pill	2	8.7%
Torque	3	13%
Install equipment	1	4.3%
Work string up and down	2	8.7%
Jarring (both)	1	4.3%
Conditioning	1	4.3%
Circulation	2	8.7%
Reduce circulation	1	4.3%
Well control	1	4.3%
SUM	23	100%

Table 10 - Determination of the threshold values

The threshold value should be estimated on the basis of the number of certain operation repetitions within the different stuck pipe freeing procedures, which belong to the group of mechanical sticking and wellbore geometry. In this case, each operation with a percentage value equal to or higher than 8.7 % will be taken into consideration for further analysis.

Having in the mind the estimated threshold values, each operation which meets the defined requirements will be included into the general procedure, where their position within the procedure is determined regarding to the calculated average values.

Operations	Operational sequences					Average values(mean)
Jarring up	3	3	4	3		3.25
Jarring down	3	1	2	2	2	2.00
Pump pill	4	6				5.0
Torque	2	2	3			2.33
Install equipment	6					6.00
Work string up and down	1	1				1.00
Jarring (both)	7					7.00
Conditioning	4					4.00
Circulation	1	4				2.50
Reduce circulation	5					5.00
Well control	1					1.00

Table 11 - Estimation of the average and standard deviation values

Based on all of the above, the operations within the procedure should be organised from the smallest to the highest obtained average values.

Mechanical sticking and wellbore geometry
Work string up and down
Jarring down
Torque
Circulation
Jarring up
Pump pill

Table 12 - Mechanical sticking and wellbore geometry general freeing procedure

When the general procedure was derived, it is very important that its results are compared with the main table of the stuck pipe mechanism. Discordance between the companies' procedures and the general procedures obtained is possible, but the operational sequences should not be changed.

In the beginning, it was observed that the general freeing procedure could not be applied completely in the case of a stuck pipe due to key seat, because applying the operation which is replaced by the code ˝Jarring up˝, will only deteriorate the situation. Due to this reason, only the first half of the procedure should be applied, after this the procedure will continue with those operations which are unique for that type of the stuck pipe mechanism.

On the basis of the results obtained and all of the above-mentioned facts, the following flowchart was developed.

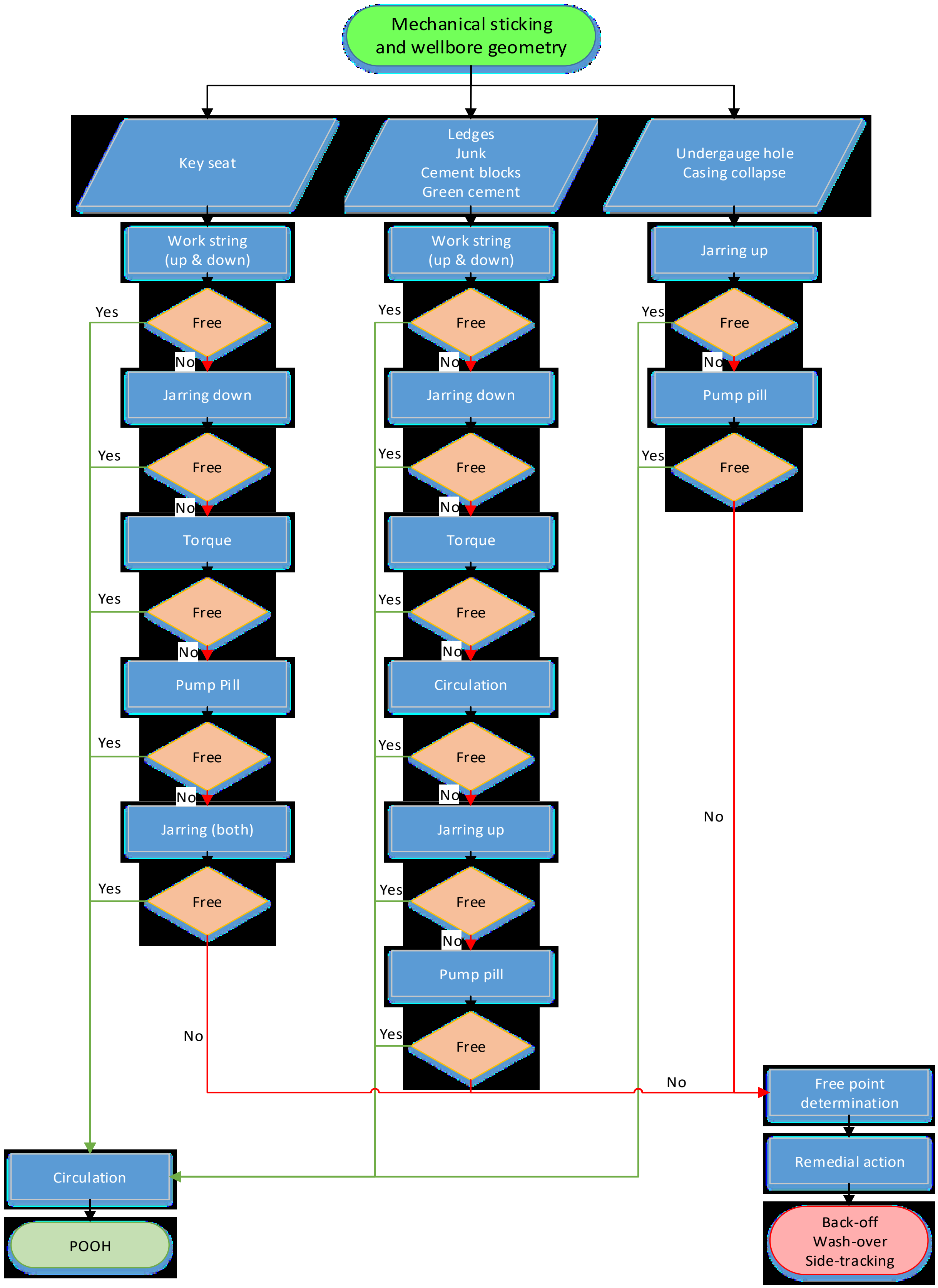

Figure 25 - Flowchart for mechanical sticking and wellbore geometry

Once the flowchart has been derived, there is still one more part of research study, which is missing. It should provide the meaning of the entire operations, which have been replaced by a coding system in the beginning, in a way which should be applicable to the driller.

On the basis of the companies' recommendations regarding the following stuck pipe subcategories, the operational codes listed below should be applied. In addition to the operational codes a short explanation of each of them is given below.

Key seat

- *Work string up and down*

The term ˝work string up and down˝ means working the string up (overpulling) and down (hanging on) for a short period of time in an attempt to reduce or eliminate sticking forces.

- *Jarring down*

The jarring down operation should be performed under maximum trip load, for the next 1-2 hours.

- *Torque*

The torque should be applied shortly after the jarring down operation is commenced and finished simultaneously with the jarring down.

Torque has the aim of creating movement at the stuck pipe point and should be applied inside the limits of 80 % make-up torque.

- *Jarring up*

Jarring up should also be continued with the maximum trip load for the next hour if the above-mentioned operations do not provide results.

- *Pump pill*

If the drill string is still in a stuck pipe condition, a low YP spacer with the volume of 6000-12000 dm^3, should be prepared at the beginning. After that, mix a PRA (pipe releasing agent) pill in a volume of 1.5 times larger than the open hole annular volume. The pill should be (0.1-0.2 SG) heavier than the actual mud used.

When the pill is set, working a drill string up and down should be performed. Moreover, the string should be slack off with 9 tonnes; right hand torque should be also applied to the value of ±0.75 turn per 300 m of total string length. After five minutes the torque should be released and the string picked up. This can move a stuck point down the hole a several tens of centimetres, until the pipe suddenly becomes free. (2)

The soaking time should be at least 20 hours, to a maximum of 40 hours.

Any pipe releasing agent pill should be spotted within four hours from the moment the stuck pipe occurs. After 16 hours, the pill should not be spotted, because it effect is negligible.

- *Jarring (both)*

The last operation in this sequence is ˝jarring both˝. This code defines the jarring up and jarring down operations, which should be performed alternately. The first hour of jarring should be performed with a light load of up to 25 tonnes and after this, the jarring forces can gradually be increased. Success is possible within 10 hours, after this period of time alternative operations should be taken into consideration.

Ledges, junk, cement block, green cement

- *Work string up and down*

Apply the same procedure for the mentioned code, such as in the case of key seat.

- *Jarring down*

Apply the same procedure for the mentioned code, such as in the case of key seat.

- *Torque*

Apply the same procedure for the mentioned code, such as in the case of key seat.

- *Circulation*

Obtaining or maintaining the circulation at all times is very important; full circulation is also desirable. On one side it can erode the formation and help in releasing the drill string. It can also reduce the hydrostatic pressure on the formation if it is possible to reduce mud density and have it make an impact on increasing jarring blows.

- *Jarring up*

Apply the same procedure for the mentioned code, such as in the case of key seat.

- *Pump pill*

At the beginning the water spacer should be pumped ahead of the pill, then a 15 % HCI pill should be pumped, plus a mud acid pill with a mixture of 12 % hydrochloric acid (HCI) and 8 % hydrofluoric acid (HF), and at the end a water spacer.

Working the pipe up and down, while the pill is soaking, is desirable.

The drill string should be free within a few minutes as the acid works quickly.

After five minutes the pill should be circulated out.

Usage of this pill is convenient for hard and compact formations.

Under-gauge hole, casing collapse

- *Jarring up*

In the first hour, the jarring operation should be performed with a light load of up to 25 tonnes, and after this the jarring forces should be increased to the maximum trip load. This operation should be performed in the next 2-3 hours.

- *Pump pill*

On the basis of the type of formation, pipe releasing agents or an acid pill should be spotted, following the procedures mentioned in the previous two subcategories, where this code existed.

The flowchart ends with two options, which are listed below, where the first one should be applied any time that the drill string is starting to release:

- Which activities should be performed if the listed operations result in releasing the stuck pipe string?

  Before the operation POOH is performed, the wellbore should be circulated for the purpose of its conditioning and cleaning. After that, the POOH operation should be performed slowly and carefully, reaming operations should be conducted whenever required, before further POOH operation is continued.

- If the drill string is still in the stuck pipe condition, which actions should be performed?

  If the all operations listed do not provide a result, a free point determination should be performed.

  On the basis of the time that has elapsed while the drill string is in a stuck pipe condition, and the time necessary for its release, remedial actions should be considered. If it is estimated that a lot of time will be required and it is will be very costly and success is not guaranteed, further actions should include back off and wash-over or side-tracking.

4.2.2 Differential sticking

Differential sticking is another mechanism which belongs to the group of the three main types of stuck pipe mechanisms. It is also the starting point of the further analysis.

The model which has already been developed for obtaining a general freeing procedure, such as in the case of mechanical sticking and wellbore geometry, will also be used for this type of stuck pipe mechanism.

At the beginning of the analysis the coding system which has been established, should again be introduced. Each of the operations within the procedures will be replaced by a certain code prior to further analysis being conducted.

Repetition of certain operations within the same procedures are observed. However only the first operations listed within the procedure should be retained, while all others should be eliminated at the beginning. Otherwise, the threshold values will not be valid and the final result, (the general procedure) may not be applicable.

Differential sticking							
Elf	Company's operational sequence	BP	Company's operational sequence	Eni	Company's operational sequence	Schlumberger	Company's operational sequence
Stop pump	1	Work string up and down	1	Work string up and down	1	Circulation	1
POOH	2	Torque	2	Torque	2	RIH	2
Jarring (both)	3	Work string up and down	3	Pump pill	3	Circulate	3
Torque	4	Well control	4	Well control	4	Torque	4
Free point determination	5	Free point determination	5	Jarring (both)	5	Pump pill	5
Pump pill	6	Pump pill	6	DST	6	Well control	6
DST	7	Work string up and down	7				
		Work string up and down	8				
		Pump pill	9				
		Well control	10				

** Red highlighting denotes eliminated operations*

Table 13 - Differential sticking procedures with a grading system

On the basis of the all procedures collated for this stuck pipe mechanism, the estimated threshold value is 8.7 %. Each operation with a value equal to or greater than 8.7 % will be considered for further analysis.

Operations	Number of repetitions	Percentage values
Stop pump	1	4.3%
POOH	1	4.3%
Torque	4	17.4%
Free point determination	2	8.7%
Pump pill	4	17.4%
Work string up and down	2	8.7%
Well control	3	13.0%
Jarring (both)	2	8.7%
DST	2	8.7%
Circulation	1	4.3%
RIH	1	4.3%
SUM	23	100.0%

Table 14 - Estimation of the threshold values

The same average values are possible, and for this reason function standard deviation should be introduced. Standard deviation is aimed at measuring the dispersion of set data from its average values (mean). If the data points are very far from the mean, simultaneously higher deviation within the data set exists.

Operations	Operational sequences				Average values (mean)	Standard deviation
Stop pump	1				1	0
POOH	2				5	3
Torque	4	2	2	4	3	1
Free point determination	5	5			5	0
Pump pill	6	6	3	5	5	1.225
Work string	1	1			1	0
Well control	4	4	6		4.67	0.943
Jarring (both)	3	5			4	1
DST	7	6			6.50	0.500
Circulation	1				1	0
RIH	2				2	0

Table 15 - Estimation of the threshold values

On the basis of the results obtained, the following table of operational sequences was developed.

Differential sticking (sequences)
Work string up and down
Torque
Jarring (both)
Well control
Free point determination
Pump pill
Back off and DST

Table 16 - Differential sticking general freeing procedure

Keeping in mind the fact that only one stuck pipe mechanism exists, the obtained result (procedure) can be taken as final and can be presented as the following:

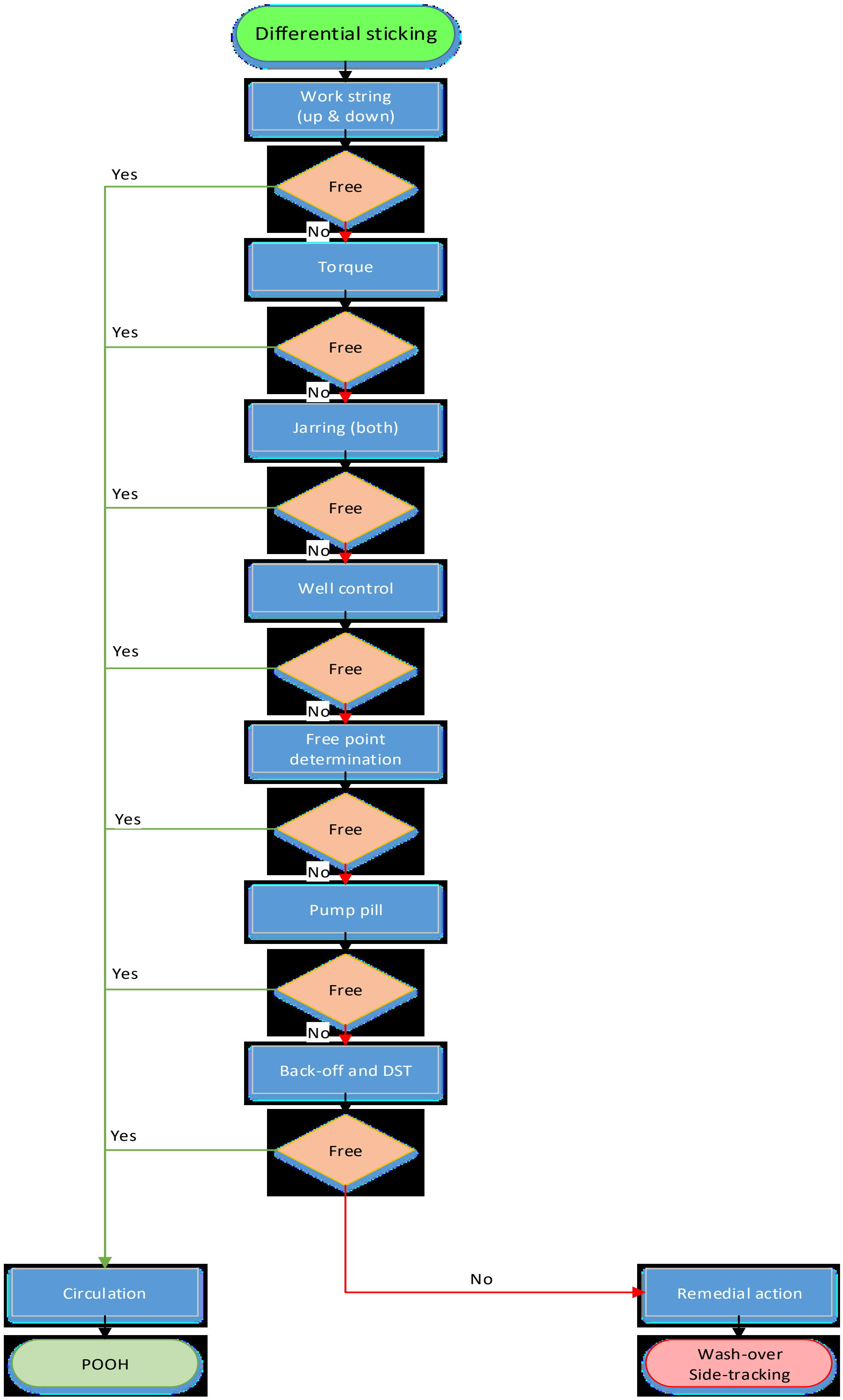

Figure 26 - Flowchart of the differential sticking freeing procedure

In the end, the performed analytical model resulted in obtaining a general procedure; however, it was missing the code meaning. The coding system introduced at the beginning, should now be replaced with the simplified and understandable filed application operations, including the following:

- *Work string*

The term ˝work string˝ refers to working the string up (overpulling) and down (hanging on) for a short period of time in an attempt to reduce or eliminate sticking forces.

- *Torque*

Within the first hour, the torque should be also applied inside the limits of 80 % make up torque. The torque should not be applied when the tapper drill pipe string is in use.

- *Jarring (both)*

The term ˝jarring both˝ defines the jarring up and jarring down operations which should be performed alternately. The first hour the jarring upward operation should be performed with a light load of up to 25 tonnes. Subsequently, over the next two hours, continue with jarring operations in both directions; forces can gradually be increased to the maximum permitted force.

- *Well control*

When the free point is determined, hydrostatic pressure reduction should be performed. Before performing hydrostatic pressure reduction, all aspects of well control must be taken into consideration. Pressure reduction is most successful if the string is under compression.

Time is also a very limiting factor; it is known that after 16 hours from the moment of the stuck pipe, spotting a pill is not a usable option.

- *Free point determination*

Being aware of the fact that the string is still in the stuck pipe condition, free point determination should be the next operation performed.

In determining the depth of the stuck pipe, the pipe stretching method and free point indicator tool should be used.

- *Pump pill*

On the basis that PRA (pipe releasing agents) pills provide the optimal results in the first four hours from the moment the stuck pipe occurs, as soon as the free point is determined, the pill should be spotted (without delay).

The procedure for preparing and spotting a PRA pill is as follows:

At the beginning 6000-12000 dm^3 of low YP spacer should be provided. The spacer should be compatible with the actual mud used and the pill.

Mix the PRA pill in a volume 1.5 times larger than the calculated annulus volume at the stuck point, with a density that is 0.1-0.2 SG heavier than the actual mud used.

The spacer and the pill should be pumped at a maximum flow rate in order to achieve soaking of the formation behind the pipe where it is stuck.

The drill string should be put into the compression with slack off four and a half tonnes below the weight of the free pipe, right hand torque should be also applied to the value of a half turn per each 300 m of pipe above the determined stuck pipe point.

After every five minutes the torque should be released and the string should be pulled up with four and a half tonnes.

An additional volume of the pill should be kept in the drill pipe and after every 30 minutes, 80 litres should be slowly pumped in order to move more pill into the borehole. [31]

Working the pipe up and down should be continued. [2]

If the pill has not been spotted in the first 16 hours from the moment the stuck pipe occurred, this operation should be skipped.

The formation soaking time should be more than 12 hours, but not longer than 40 hours.

- *Back off and DST*

If all the operations listed above do not provide a satisfactory result, and there is no risk of formation fluid inflow in the borehole, the following procedure, should be conducted:

- The back-off operation should be performed as deeply as possible
- The DST tool should be run into the hole and connected with a fish. The tester valve should be open for a short time (not more than one minute), in order to permit formation fluids inflow into the wellbore and it should relieve differential pressure on the formation.

4.2.3 Solid induced pack-off

Solid induced pack-off is the final stuck pipe mechanism within the group of three main types of stuck pipe mechanisms, and is also the starting point of further analysis.

The model which has already been developed for obtaining general freeing procedures can also be applied here. In regard to possible deviations from the model, attention will be given in order to avoid all uncertainties, making the final stuck pipe freeing procedure obtained, applicable.

Before commencing analysis, all the collated freeing procedures used by the companies for different stuck pipe mechanisms which belong to the group of solid induced pack-off should be replaced once again by a coding system.

Solid induced pack-off														
Unconsolidated formations		Fracture and fault formations	Mobile formations				Reactive formations			Naturally over-pressured shale collapse = Unconsolidated formations		Induced over-pressured shale collapse	Tectonically stressed formations	Poor hole cleaning
			Salt		Shale									
Schlumberger	Drilling formulas	Other sources	Elf	Other sources	Elf	Other sources	Elf	BP	Schlumberger	Schlumberger	Drilling formulas	Other sources	Other sources	BP
Reduce circulation	Circulation	Jarring down	Back off	Pump pill	Circulation	Torque	Circulation	Circulation	POOH	Reduce circulation	Circulation	Reduce circulation	Circulation	Circulation
Stop pump	Torque	Jarring up	Pump pill	Pump pill	Well control	Jarring (both)	Circulation	Torque	Reduce circulation	Stop pump	Torque	Torque	Torque	Work string up and down
Well control	Jarring (both)	Circulation		Pump pill	Jarring (both)	Pump pill	Pump pill	Well control	Stop pump	Well control	Jarring down	Jarring down	Jarring down	Circulation
Torque	Circulation			Pump pill			Work string up and down		Well control	Torque	Jarring up	Jarring up	Jarring up	Circulation
Work string up and down				Well control			Pump pill		Torque	Work string up and down	Circulation	Circulation	Circulation	
Well control							Jarring		Work string up and down	Well control				
Work string up and down									Well control	Work string up and down				
Torque									Work string up and down	Torque				
Jarring (both)									Torque	Jarring (both)				
Circulation									Jarring (both)	Circulation				
									Circulation					

** Other sources - under this term the collated stuck pipe freeing procedures from other sources is defined (Sugar land, Drilling formulas, Stuck pipe prevention)*

Table 17 - Solid induced pack-off procedures of companies

When the coding system was developed it became clear that for unconsolidated, mobile and reactive formations, more than one different procedure existed for releasing a stuck pipe string.

It was also observed that both of the collated stuck pipe freeing procedures for the reactive formation were very different and that a unique procedure was not able to be developed. For this reason, but according to Schlumberger's recommendation, the same procedure with the added first operational-code ˝POOH˝ such as in the case of the stuck pipe in the “Naturally over pressure and unconsolidated formations”, will be used.

Based on the number of available procedures, the threshold value for an unconsolidated and reactive formation was determined to be 11 %. This means that each operation with a percentage value of less than 11 % will be discarded.

Operations	Number of repetitions	Percentage values
Stop pump	1	11%
Well control	1	11%
Torque	2	22%
Work string up and down	1	11%
Jarring (both)	2	22%
Circulation	2	22%

Table 18 - Estimation of the threshold values for an unconsolidated formation

Operations	Number of repetitions	Percentage values
POOH	1	7%
Stop pump	1	7%
Well control	2	14%
Torque	2	14%
Work string up and down	2	14%
Jarring (Both)	2	14%
Circulation	3	21%
Pump pill	2	7%

Table 19 - Estimation of the threshold values for a reactive formation

For estimation of the average value, a grading system should be introduced. The purpose of the average value is the estimation of the operational sequences within the procedure.

Unconsolidated formations			
Schlumberger	Company's operational sequence	Drilling formulas	Company's operational sequence
Reduce circulation	1	Circulation	1
Stop pump	2	Torque	2
Well control	3	Jarring (both)	3
Torque	4	Circulation	4
Work string	5		
Well control	6		
Work string up and down	7		
Torque	8		
Jarring (both)	9		
Circulation	10		

** Red highlighting denotes eliminated operations*

Table 20 - Introduction of the grading system for an unconsolidated formation

Reactive formations					
Elf	Company's operational sequence	BP	Company's operational sequence	Schlumberger	Company's operational sequence
Circulation	1	Circulation	1	POOH	1
Circulation	2	Torque	2	Reduce circulation	2
Pump pill	3	Well control	3	Stop pimp	3
Work string up and down	4			Well control	4
Pump pill	5			Torque	5
Jarring	6			Work string up and down	6
				Well control	7
				Work string	8
				Torque	9
				Jarring (both)	10
				Circulation	11

Table 21 - Introduction of the grading system for a reactive formation

For further analysis, instead of the code ˝Reduce circulation˝, the code ˝Circulation˝ will be used. Because there is circulation, the only difference is in the volume of the fluid which is being pumped.

Furthermore, only operations which are mentioned once within the same procedure should be retained, as per the previous analysis.

Operations	Operational sequences		Average values
Circulation	1	1	1
Stop pump	2		2
Well control	3		3
Torque	4	2	3
Work string	5		5
Jarring (Both)	9	3	6

** Red highlighting denotes eliminated operations*

Table 22 - Estimation of the average values for an unconsolidated formation

Operations	Operational sequences			Average values	Standard deviation
POOH	1			1	0
Stop pump	3			3	0
Well control	3	4		3.50	0.50
Torque	2	5		3.50	1.50
Work string	4	6		5	1
Jarring (both)	6	10		8	2
Circulation	1	1	2	1.33	0.47
Pump pill	3			3	0

Table 23 - Estimation of average and standard deviation values for a reactive formation

Keeping in mind that the threshold value was determined in the previous step, based on the average values and introduced standard deviation function, where more than one of the same average value exists, the following procedures were obtained.

Unconsolidated formations
Circulation
Torque
Jarring (both)
Circulation

Table 24 - Unique freeing procedure for an unconsolidated formation

Reactive formations
Circulation
Well control
Torque
Work string
Jarring (both)

Table 25 - Unique freeing procedure for a reactive formation

The unique procedure obtained for an unconsolidated formation has at its conclusion one additional operation –just like both of the collated companies' freeing procedures – the listed operations finish with a circulation.

Moreover, when stuck pipe occurs in a naturally over-pressured shale collapse formation, based on the companies' recommendations, the same freeing procedure should be applied such as in the case of an unconsolidated formation.

Based on what has been previously stated, the mobile formation is the last stuck pipe mechanism within the group of solid induced pack-off where more than one different freeing procedure exists.

At the beginning, under the term of "mobile formation", two different types of formations are defined – salt and shale formation.

In the case of salt, Elf recommends immediately performing a back-off operation, before any other operations for releasing the drill string are performed, while the category ˝Other sources˝ suggests spotting different types of pills, before the operation back off is commenced. On the basis that it is always preferable to make an attempt to free the drill string prior to carrying out a back-off operation, in order to release the stuck pipe string, the Elf procedure should be reserved for later.

In the case of stuck pipe in mobile-salt formations, the following procedure should be performed.

Salt formations
Pump pill
Pump pill
Pump pill
Pump pill
Well control

Table 26 - Unique freeing procedure for salt formations

For shale formation, the Elf procedure is more acceptable, as Elf provide a unique procedure for shale formations, while the category ˝Other sources˝ has a unique procedure for both salt and shale formations. For this reason, the Elf procedure will be considered as being more applicable.

Shale formations
Circulation
Well control
Jarring (both)

Table 27 - Unique freeing procedure for shale formations

When each stuck pipe mechanism within the group of solid induced pack-off is defined with its unique procedures, the known grading system should once again be introduced. It is worth mentioning that the purpose of the grading system is to obtain a general procedure for all stuck pipe mechanisms that belong to the group of solid induced pack-off.

Solid induced pack-off																	
				Mobile formations													
Unconsolidated formations	Company's operational sequence	Fracture and fault formations	Company's operational sequence	Salt	Company's operational sequence	Shale	Company's operational sequence	Reactive formations	Company's operational sequence	Naturally over-pressured shale collapse	Company's operational sequence	Induced over-pressured shale collapse	Company's operational sequence	Tectonically stressed formations	Company's operational sequence	Poor hole cleaning	Company's operational sequence
Circulation	1	Jarring (both)	1	Pump pill	1	Circulation	1	Circulation	1	Circulation	1	Reduce circulation	1	Circulation	1	Circulation	1
Torque	2	Circulation	2	Well control	2	Well control	2	Well control	2	Torque	2	Torque	2	Torque	2	Work string up and down	2
Jarring (both)	3					Jarring (both)	3	Torque	3	Jarring (both)	3	Jarring (both)	3	Jarring (both)	3	Circulation	3
Circulation	4							Work string up and down	4	Circulation	4	Circulation	4	Circulation	4		
								Jarring (both)	5								

** Red highlighting denotes eliminated operations*

Table 28 - Solid induced pack-off with a grading system

Before the further analysis is performed, an overview of all the stuck pipe freeing procedures within the group of solid induced pack-off should be conducted. Each stuck pipe mechanism whose procedure deviates from the others should be separated; otherwise the developed procedure will not be usable.

The first discordance is noted in the case of salt formation whose freeing procedure requires only pumping with different types of pills, instead of performing any other operations until the stuck pipe string is freed. If its freeing procedure is not excluded at the beginning, it will have an impact on further statistic analysis. The effectiveness of the unique freeing procedure obtained will be significantly reduced, and will also not be applicable in the case of a salt formation.

It is accepted that only the first mentioned operation within the procedure will be used for statistic analysis; all other repetitions will not be utilised.

As part of the analysis, the operation-code “Circulation” was used instead of ˝Reduce circulation˝ as circulation existed with the only difference being in the pump rate.

The threshold value for the previous two main types of stuck pipe mechanisms was 8.7%. This means that each operation with a threshold value which is equal to or greater than 8.7% was used for further analysis. The obtained value can also be a suitable fit for solid induced pack off, simultaneously becoming unique for the three main types of stuck pipe mechanisms.

Operations	Number of repetitions	Percentage values
Well Control	2	8.33%
Circulation	8	33.33%
Torque	5	20.83%
Work string	2	8.33%
Jarring (both)	7	29.17%
SUM	24	100.0%

Table 29 - Determination of the threshold values

When all the conditions were met and the unique procedure for each stuck pipe mechanism was obtained, the average value for all of them was able to be determined.

Operations	Operational sequences								Average values
Well control		2	2						2
Circulation	1	2	1	1	1	1	1	1	1.11
Torque	2	3	2	2	2				2.2
Work string up and down	4	2							3
Jarring (both)	3	1	3	5	3	3	3		3

Table 30 - Estimation of the average values

On the basis of the obtained average values, the operations within the final procedure should be organised from the lowest to the highest values.

Solid induced pack-off
Circulation
Torque
Jarring (both)
Circulation

Table 31 - Solid induced pack-off general freeing procedure

Most of the collated procedures finished with the operation-code "Circulation". For this reason, the same operation was included in the general developed procedure.

Once the general procedure has been derived, it is desirable to have one more overview before the flow chart is developed. The purpose of this is to find discordances between the companies' procedures and the developed general procedure, if they exist.

As discordances were not observed, a flowchart such as the following was obtained.

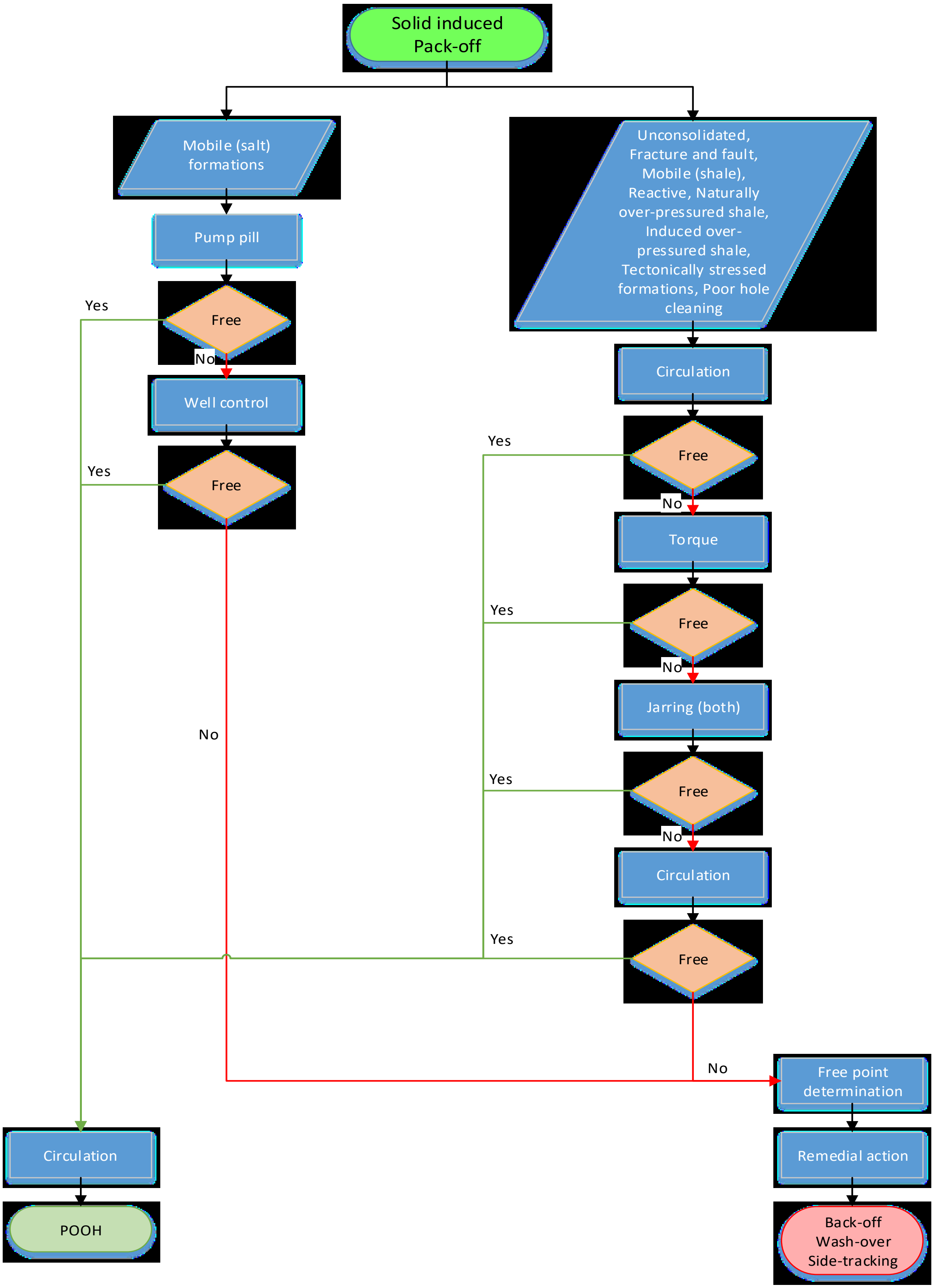

Figure 27 - Flowchart for solid induced pack-off

Now, when the general procedure has been derived on the basis of all the performed analyses, the final phases imply the conversion of the general freeing procedure's subcategory codes into a simplified and understandable plan for action.

Mobile formation (salt)

- *Pump pill*

The code ˝pump pill˝ defines preparing and pumping a fresh water pill to dissolve the salt in the stuck pipe zone, which is usually in the BHA. An additional volume of 3 m^3 pill should also be kept in the string for reserve. Detergent may be added to the pill with the purpose of removing any mud film from the borehole wall. In the case that oil-based mud has been used in the hole pump a viscous weighted spacer ahead of the pill should be added (e.g. XC polymers and barite). During spotting a pill with the maximum value of the overpull should be held. After two hours, if the freshwater pill has not given any results, a second pill should be spotted.

- *Well control*

In the case of the mentioned type of formation, all aspects of the well control should be taken into consideration. Very often the pill is a lower density than the actual mud used and simultaneous formation inflow is possible.

Unconsolidated, fracture and fault, mobile (shale), reactive, naturally over-pressured shale, induced over-pressured shale, tectonically stressed formations and poor hole cleaning

- *Circulation*

At the beginning the pump rate should be reduced and circulation should be continued with a low pressure of 20-25 bar.

High circulation capacity should not be applied as this can pack harder accumulated formation material, and subsequent operations for freeing the stuck pipe will become more difficult.

- *Torque*

The torque should be applied inside the limits of 80 % make-up torque.

Rotation, if established, may help with disturbing the packed-off formation material around the drill string.

- *Jarring (both)*

Depending on the direction of string movement and bit position at the moment of the stuck pipe, jarring up or jarring down should be applied, simultaneously with or without torque. Jarring forces should be increased gradually up to the maximum trip load.

It is assumed that operations performed with a jar are most effective within the first three to four hours from the moment that the stuck pipe occurred; after 12 hours, the chances of releasing the drill string with a jar are minor.

When to apply torque and/or jarring (both)?

- If a stuck pipe has occurred while drilling or tripping out of the hole, the maximum allowable torque in combination with jarring down should be applied.
- In the case that the stuck pipe has happened while running in the hole, jarring up should be applied, without torque.

5 Application of model on an artificial data set

The main purpose of this chapter is to confirm the practical usage of everything covered until now. The chronological overview of this study should pass very quickly from the moment that different types of stuck pipe mechanisms are presented, through to the different stuck pipe freeing procedures gathered, until the analytical model is developed, resulting in obtaining the general stuck pipe freeing procedures.

The obtained results, in this case the general freeing procedures, are the most important part of this work, whose applicable purpose is linked to determining the correct cause of the stuck pipe situation and consequently selecting the appropriate general freeing procedure.

5.1 Artificial data creation

Based on the gathered data, from the well UK-1 (Ulcinj Onshore), which was drilled 25 years ago in Montenegro, the author came upon the idea (due to the lack of sensor data, but on the basis of geo-log data), to create an artificial mudlogging data set. A time interval of two hours is constructed where the data frequency of five seconds was chosen. At the beginning of this interval a tripping operation was performed. The next 14 hours of operational data was shrunk into 60.08 minutes. This means that all of the operations performed were adjusted to a time interval of two hours. For the purpose of further analysis some of the operations performed by the crew have been invented and the situations have been adapted for the purpose of the work and available data.

5.2 Review of bottom hole assembly and operational parameters prior to the stuck pipe situation

The range of interest is from the last cased and cemented hole section with a casing shoe at a depth of 4296.8 m. Further, the drilling was continued until a depth of 4623 m, where due to bit wear (gauge lost) the decision was made to trip out of the hole.

The bottom hole composition is presented as the following:

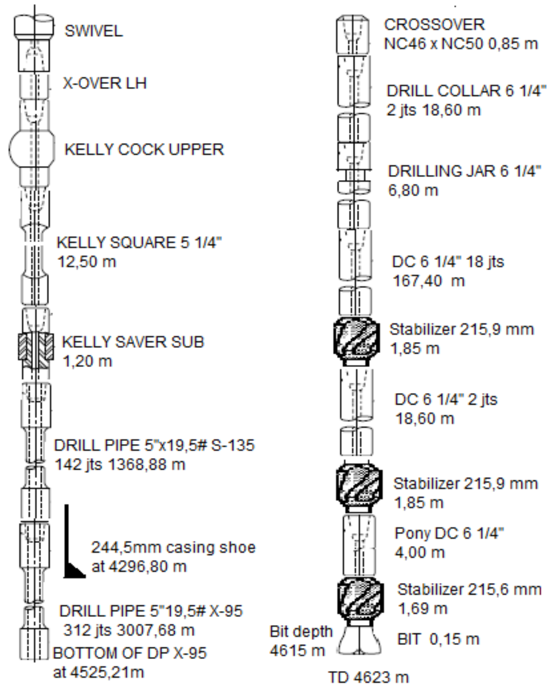

Figure 28 - Bottom hole assembly

Regarding the type of formation, it was characterised by a series of faults with a small amount of naturally caved fracture limestone and dolomite material at the shale shakers while drilling, simultaneously causing rotary torque oscillations. Significant mud losses were not noticed.

After the bit was changed, the tripping operation was continued, without rotation and circulation, until a depth of 4615 m where due to the frequent overpull and hanging on, circulation and rotation were established for the purpose of wellbore conditioning. The flow rate was nearly constant at 1470 l/min with a pump pressure of 108 bar. Also, significant oscillations into the RPM and torque were not observed. After a short time, the tripping operation was continued, until the depth of 4620 m, where hook load and torque oscillations were observed until the stuck pipe occurred.

5.3 The stuck pipe freeing procedure performed by the company

Keeping in mind everything that has been previously mentioned in regard to the depth of 4623 m and tripping activities, this section continues with a review of crew activities performed shortly before and at the moment when the stuck pipe occurred.

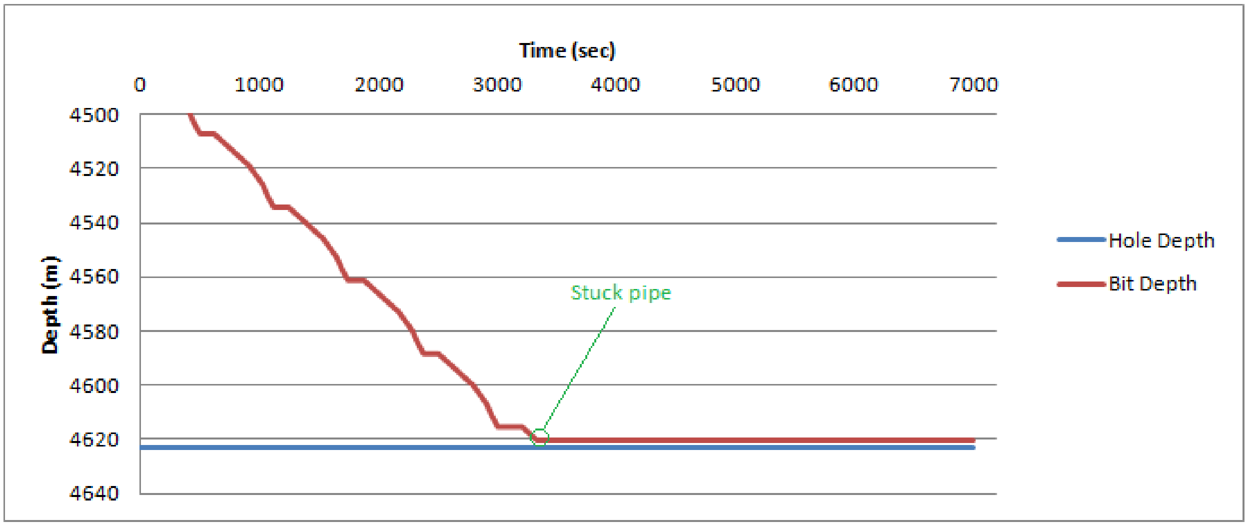

Figure 29 - Time versus depth

The first indicator of the possible stuck pipe condition is the inability to reach the drilled depth of 4623 m.

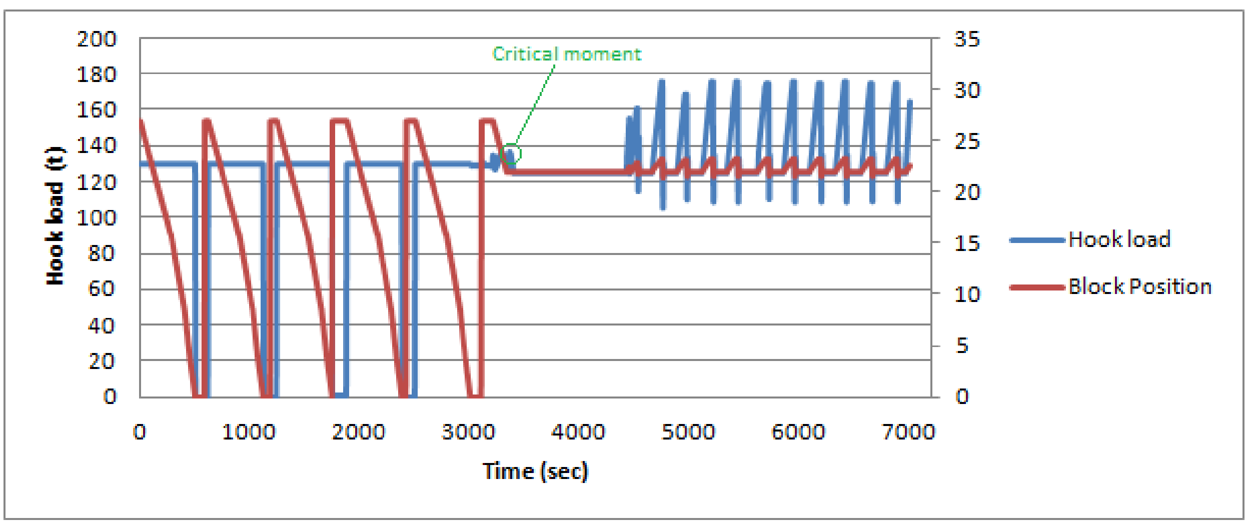

Figure 30 - Hook load and block position vs. time

Before the critical, possible ˝stuck pipe˝ moment, some of the oscillations of the hook load were mentioned. From that moment, the drill string weight dropped from the normal weight of 130 tonnes to a weight of 125 tonnes.

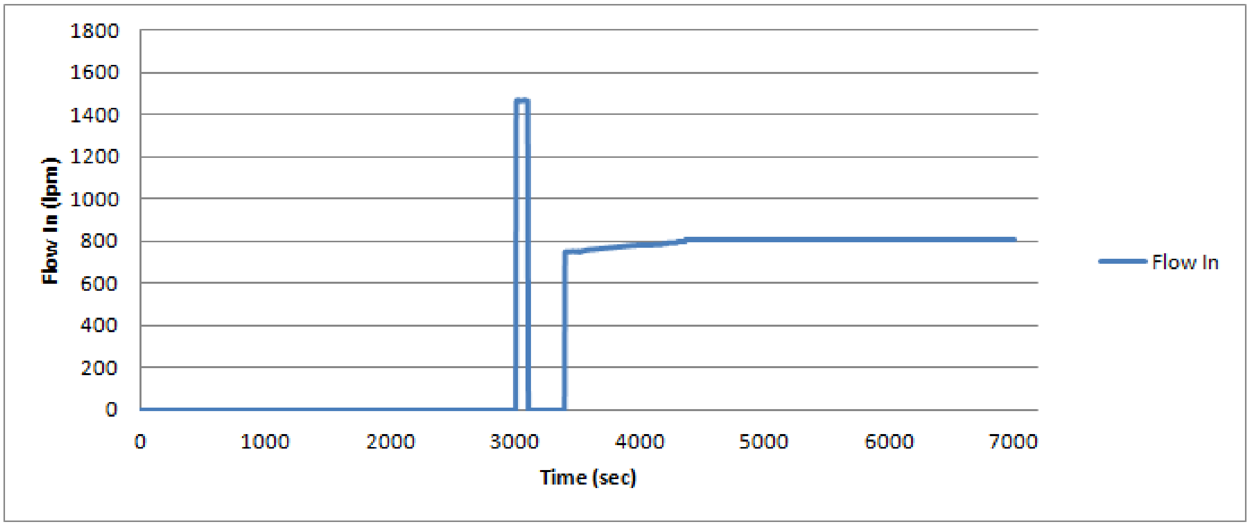

Figure 31 - Flow in vs. time

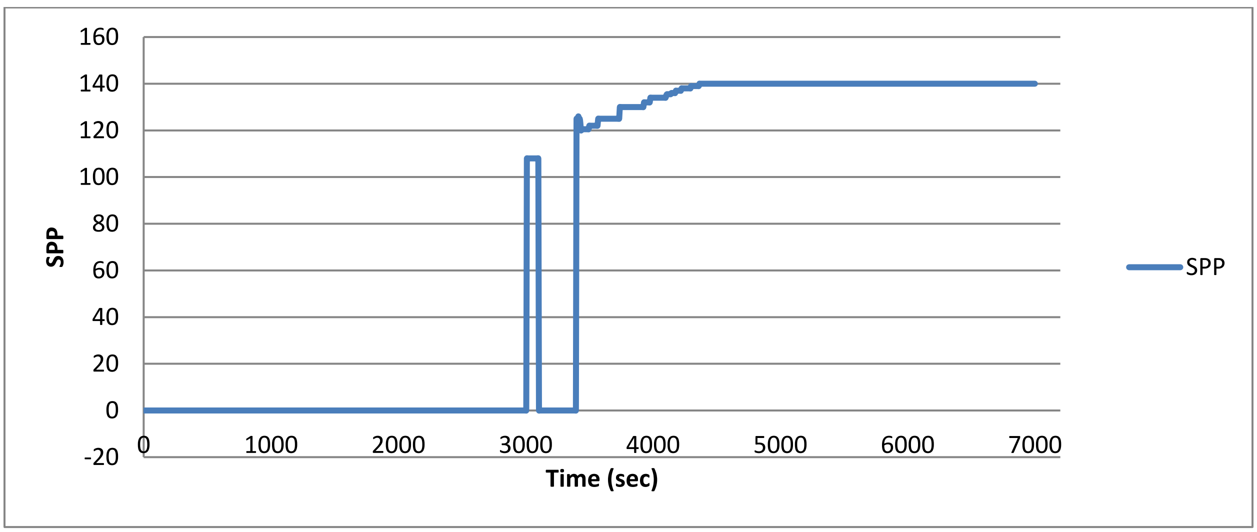

Figure 32 - Stand pipe pressure vs. time

When the tripping operations could not be continued, the crew started the mud pump, which resulted in drastically increased stand pipe pressure. With a flow in of 750 l/min the stand pipe pressure (SPP) was 125 bar. Applying a higher pump rate caused a further increase in SPP. After a while, in order to confirm the stuck pipe situation, the crew decided to establish rotation, which caused a drastic increase in torque after only a few turns.

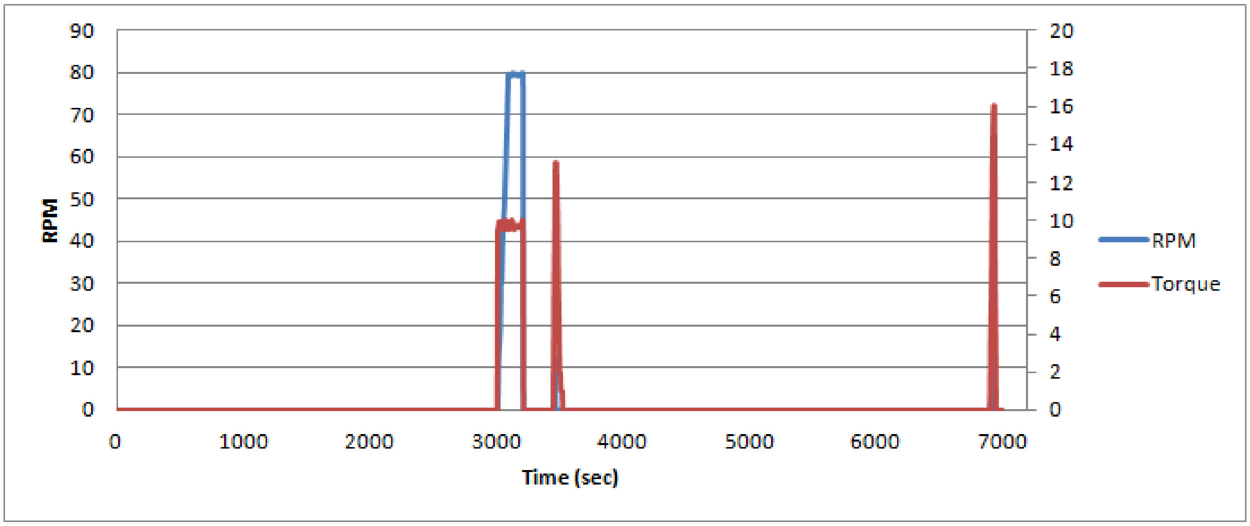

Figure 33 - RPM and torque vs. time

The rotation was switched off and the torque was gradually released.

5.3.1 Attempts to release the stuck pipe string

Under the current stuck pipe situation, the crew decided to maintain the circulation, increasing flow rate, but simultaneously the stand pipe pressure (SPP) went up. Flow rate was being increased until the stand pipe pressure limit of 140 bar was reached. The flow rate of 820 l/min was kept constant, keeping the SPP at 140 bar.

The second attempt started with a jarring operation. After the jar was activated, the operation started with applying a jarring blow of 36 tonnes, which was gradually increased up to 51 tonnes. After a while, due to the unsatisfactory results, the crew decided to perform further operations in order to release the stuck pipe string.

The third attempt, and also the last in regard to the available data, was an attempt to establish rotation once again, however, the torque drastically increased and the jarring operations were continued.

5.4 The application of the general freeing procedure for releasing the stuck pipe string

Based on the short description of the performed operations, until the problem appeared from the previous section of ˝Review of bottom hole assembly and operational parameters prior to the stuck pipe situation˝ of this phase, the author came up with the idea of performing one of the general stuck pipe freeing procedures derived on the actual problem. The starting point was the same as the company’s, providing constant monitoring of the drill string behaviour and drilling parameters in comparison to the stuck pipe freeing procedure performed by the company.

Firstly, the most limiting factor which defines the success of the freeing of the stuck is the time that elapses from the moment the stuck pipe occurs. Then the stuck pipe freeing procedure performed is tightly linked with the determination of the particular stuck pipe mechanisms which have caused the stuck pipe condition. Applying an inappropriate freeing procedure will further complicate the situation, simultaneously reducing the chances of releasing the stuck pipe string.

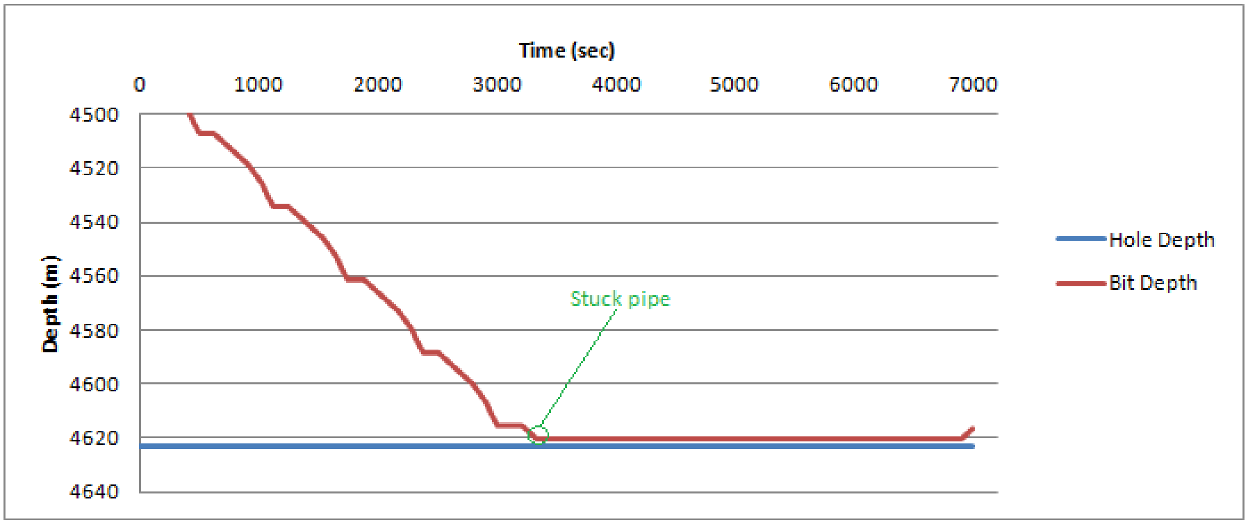

Figure 34 - Depth vs. time

The author reconstructed the situation from a depth of 4620 m where further tripping activities could not be continued.

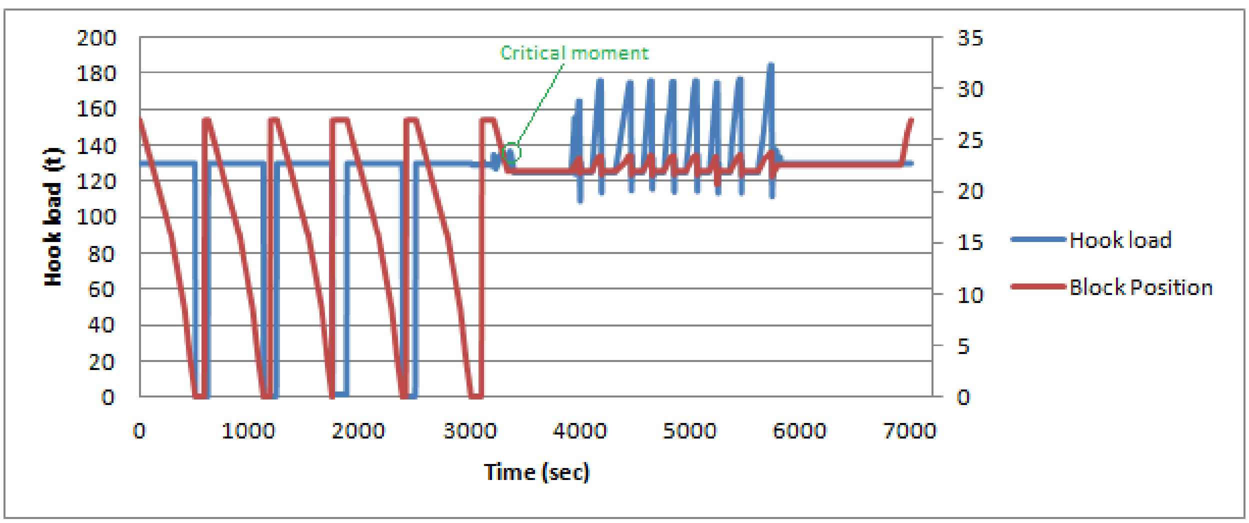

Figure 35 - Hook load and block position vs. time

The hook load oscillations prior to the critical ˝stuck pipe˝ moment are visible in the above figure. Moreover, after a very short period of time the hook load dropped and stayed at the constant value of 125 tonnes, due to the fact that the weight of the string was carried partly by the formation.

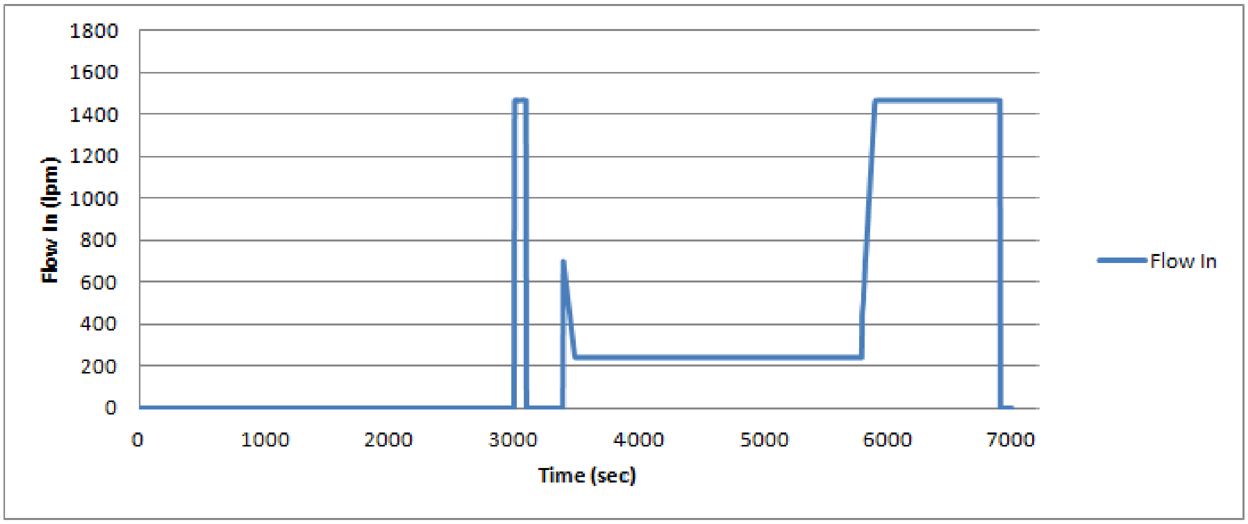

Figure 36 - Flow rate vs. time

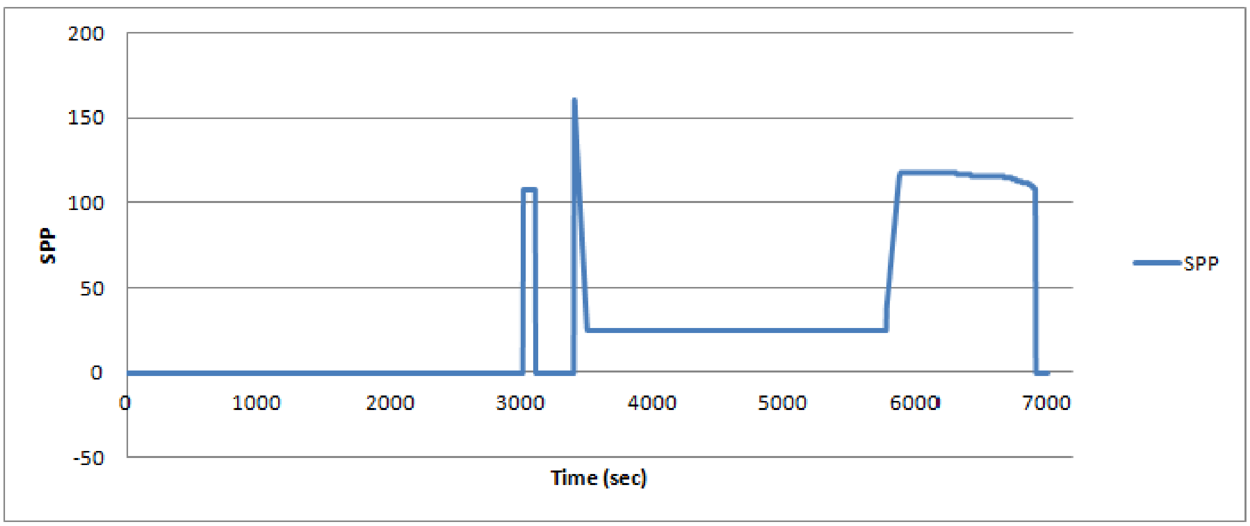

Figure 37 - Stand pipe pressure vs. time

The first thing that should be done in this situation is trying to establish circulation.

When the pump was switched on, the stand pipe pressure drastically increased to 160 bar under the flow rate of 700 l/min.

The available lithological and geophysical data, separated cuttings material at the shale shakers, behaviour of the drill string and rig sensor data before the stuck pipe occurred, are all helpful parameters for the determination of the stuck pipe mechanism.

During the previous drilling activities, huge quantities of separated caved material with sharp edges were separated at the shale shakers. Also, the hook load oscillations near the drilled depth while tripping operations were being performed, and the significant increase in the stand pipe pressure (SPP) under a low flow rate, lead to the conclusion that the stuck pipe is probably due to a fracture and fault formation.

Having in the mind that fracture and fault formation belong to the third sub-category of the solid induced pack-off mechanisms, an attempt will be made to release the stuck pipe string in accordance with the previously derived general stuck pipe freeing procedure.

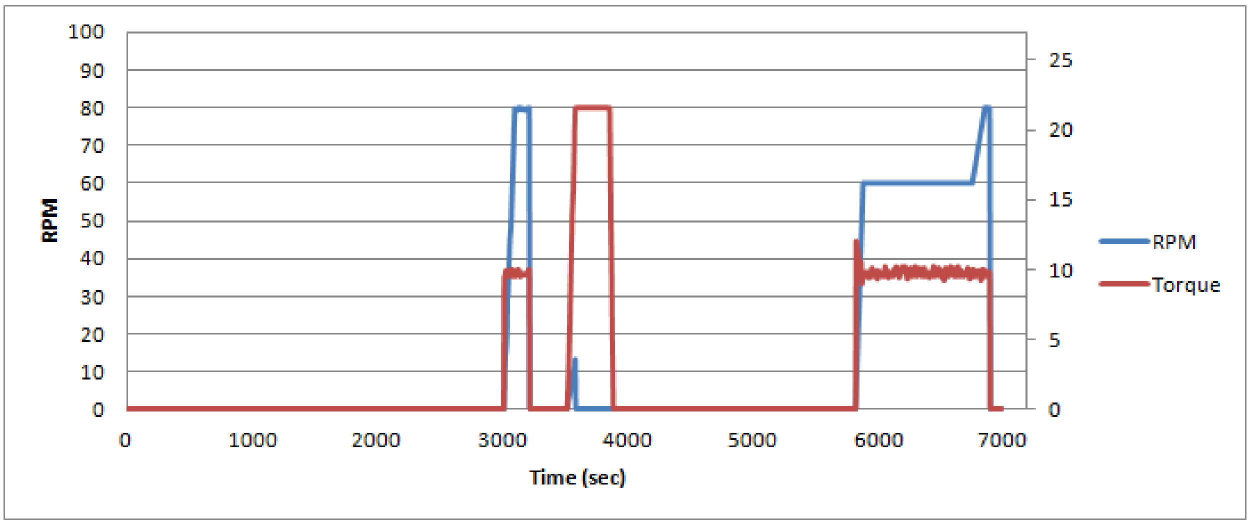

Figure 38 - RPM and torque vs. time

5.4.1 Attempts to release the stuck pipe string

On the basis of the determined stuck pipe mechanism, the following procedure for the releasing of the stuck pipe string will be applied.

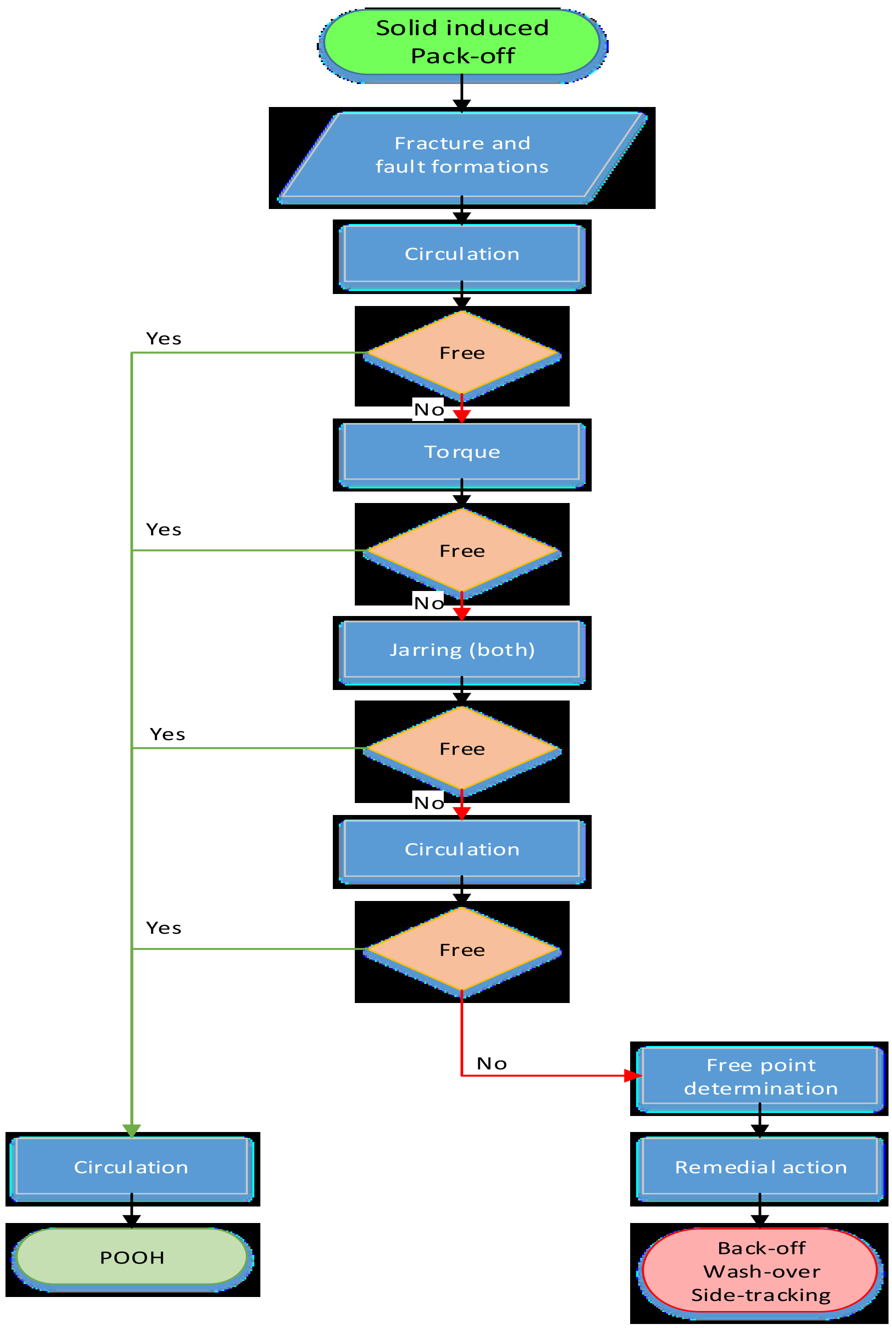

Figure 39 - Flowchart for fracture and fault formations

Initially the stand pipe pressure should be reduced up to 20-25 bar and the circulation should be kept constant the whole time while the string is in the stuck pipe condition.

When the flow rate was reduced to 243 l/min the stand pipe pressure simultaneously decreased to 25 bar.

The next operation is rotation establishment. When rotation was applied, the torque drastically increased, which is also one of the indicators confirming that the fracture and fault formation is the cause of the stuck pipe.

The RPM was increased until the torque reached the limit of 80 % of the make-up tool joint torque. The rotation was stopped and the torque was held for the next five minutes, but unfortunately without results.

According to the derived stuck pipe freeing procedure, the third operation should start with jarring. Keeping in mind the fact that the stuck pipe occurred while running in the hole, the jarring up under maximum trip load should be applied without torque.

In the beginning the drill string was pulled up in order to activate (unlock) the drill jar and the activities started with a created blow of 40 tonnes, which was gradually increased up to 60 tonnes. After a while it resulted in slowly releasing the stuck pipe string.

Under the lower overpull the block position started to slowly increase. Also, the hook load was oscillated below and above the normal weight of 130 tonnes due to caved material being transported up to the surface.

According to the procedure, a further operation is ˝circulation˝. This term includes circulation, rotation and reciprocation in order to remove the caved material from the wellbore up to the surface.

The flow rate was gradually increased with an appropriate increase in the stand pipe pressure.

When the hook load was stabilised at 130 tonnes, rotation was applied. In the beginning torque was 12 kNm and over time rotation was increasing, while torque was decreasing.

Also under the normal flow rate of 1470 l/min the stand pipe pressure was 118 bar since the annulus was still loaded with caved material which was being carried up to the surface.

The procedure finished with the operation POOH (pull out of the hole). According to good drilling practice, after a stuck pipe situation the string should be POOH in order to check the bottom hole assembly, before further drilling activities are conducted.

5.5 Summary of the company's procedure in correlation to worldwide acceptable practice

Initially, at the first signs of a stuck pipe situation, and when full circulation cannot be established, the flow rate should be reduced until stand pipe pressure reduction of about 20-25 bar is achieved. This is according to good oil field practice recommendations, which the company did not follow. Applying higher stand pipe pressure, when the stuck pipe is due to a cave of natural fracture and fault formation, will cause harder pack off formation material around the drill string, reducing the chances of it being released later on.

Secondly, a lot of time elapses before the jarring operation is performed. Based on the general accepted recommendation, the best result can be achieved in the first three to four hours from the moment that the stuck pipe occurs; after 12 hours, the chances of success are negligible. Also the jarring operation was not performed completely correctly, because the limit of the maximum trip load was not achieved.

Moreover, while releasing the stuck pipe string by trying to apply torque, the torque limit which is 80 % of the makeup tool joint, was not achieved.

Based on these abovementioned points, it can be concluded that the operations applied were not in accordance with good oil field practice, which is the most likely reason that the operations performed did not result in releasing the stuck pipe string.

Conclusion

The appropriate response to a particular problem is the key to success. The magnitude of the problem is tightly linked with the understanding of it, performing the predefined procedure in an appropriate manner, which should reduce its adverse outcomes as much as possible, and afterwards providing suitable working conditions for achieving the previously defined aim.

Stuck pipe was the particular problem of this study due to its specificity to be predicted in advance. However, when it occurs, finding a suitable answer to this actual problem is a priority.

It was confirmed that the chances of releasing a stuck string decreases over time, so utilisation of the appropriate procedure is one of the segments in the overall process which defines the success of releasing the stuck pipe string.

Therefore, the main focus of this study was developing a suitable analytical model, whose purpose was based on the performed analysis, searching for similarities between a large number of different collected stuck pipe freeing procedures for each stuck pipe mechanism. Then their organisation in a manner which resulted in deriving the three main general stuck pipe freeing procedures: mechanical sticking and wellbore geometry, differential sticking and solid induced pack-off, with few additional sub-categories.

The general stuck pipe freeing procedures obtained are very simple, but on the other hand, they are very effective. Each procedure is defined by the sequence of operations with a clear recommendation of the actions which should be performed by the driller at the moment of the stuck pipe.

The estimated threshold value of 8.7 % was appropriate for the all three main types of stuck pipe mechanism. This means that each operation which reached the estimated threshold value was included in the general procedures. The obtained value is not fixed, because it depends on the number of different stuck pipe freeing procedures that will be gathered.

It is also important to mention, that the success of releasing the stuck pipe string depends on the mechanism which caused the stuck pipe condition. Moreover, it defines which one of the general stuck pipe freeing procedures will be applied.

Finally, the method was proven to be successful and the stuck pipe string was released. This was based on the artificial data system, which should later be confirmed on the real data set in practice.

Recommendations

Being aware that the general stuck pipe freeing procedure obtained was successfully used on the artificial data set and the drill string was released, now the most important objective will be testing the entire general freeing procedures on a real data set.

Further improvement could be achieved with the extension of the different stuck pipe freeing procedures collected; speaking with contractors, operators and service companies.

One of the future recommendations should also be the usage of a more sophisticated statistical model, while performing these kinds of analysis.

In conclusion, a stuck pipe is still a huge problem in the oil industry, and the obtained model should be the first step toward a future solution to the present problem. Additionally, it is always important that a driller at the rig site has access to quality procedures which will guarantee a high level of success for the release of a stuck pipe string.

Nomenclature

F Differential sticking force [N]

ΔP Differential pressure [kPa]

A Area [m^2]

f Coefficient of friction, dimensionless

V_s Slip velocity [m/min]

μ_a Apparent viscosity [Pa-s]

ρ_m Mud density [kg/dm^3]

d_p Particle diameter [mm]

ρ_p Particle density [kg/dm^3]

PV Plastic viscosity [cP]

τ_o Shear stress [Pa]

V fluid velocity [m/s]

V_a Annular velocity [m/min]

V_s Slip velocity [m/min]

q Circulating rate [m^3/s]

d_1 Outside diameter of pipe [m]

d_2 Hole diameter or inside diameter of casing [m]

n Power-law exponent, dimensionless

Δp Pressure drop [Pa]

I Power-law consistency index [Pa·s^n]

L Length of annulus [m]

h Local annular clearance or slot height [mm]

$|y|$ Absolute value of y coordinate

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