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THE EFFECTS OF DRILLING FLUID PARAMETERS ON DIFFERENTIAL STICKING

BSc Thesis

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1. INTRODUCTION

Stuck pipe incidents are one of the most common problems in the drilling industry, approximately every third reported drilling problem is resulted from stuck pipe. *(Reid, Meeten, Way 2000)* Industry estimates claim that costs related to stuck pipe may exceed several hundred million US dollars annualy. *(Muqeem, Weekse, Al-Hajji 2012)* Cases differ from minor cases to major complications, which events could lead to significant amount of lost time and associated costs. As a worst case scenario, sticking could even lead to the complete loss of a well. As for the prevention, it is essential to understand the causes and symptoms related to the different types of sticking, as each cause needs a different intervention. An inappropriate reaction could easily worsen the situation, so evaluating the events leading to stuck pipe situations is crucial. *(Drilling Fluids Engineering Manual 2006)*

The theory of pressure-differential sticking was defined by C. S. Penfield, formerly Drilling Superintendent for Shell Oil Company. *(Helmick, Longley 1957)* Differential sticking became a main concern when the industry encountered abnormal pressures drilling exploration wells in the Gulf of Mexico, where high overbalance was needed. At the same time, low-angle directional drilling in offshore environment was carried out frequently, which meant longer sections of permeable formations being exposed. Another significant increase in differentially stuck pipe incidents happened in the late 1990s, as high angle and extended reach trajectories became common. Higher inclination meant higher mud weight for stability, higher contact force on the inclined pipe and larger contact surfaces as well, when permeable zones were penetrated. Freeing a stuck pipe in high angle wellbores is far more difficult compared to a vertical hole, while the cost of sidetrack operations also increased. *(Dupriest, Elks, Ottesen 2011)* As more and more reservoirs become depleted, the number of wells drilled with high overbalance pressures will rise, therefore maintaining the concerns over differential sticking. *(Reid, Meeten, Way 2000)* Hence the thorough understanding of the mechanics of differential sticking and how to prevent these incidents became highly important in the drilling industry.

This thesis investigates the drilling parameters related to differential sticking in general, then examines the effects of drilling fluid parameters in details, reviewing technical literature. Preventive actions and stuck pipe freeing methods are described as well. Later on, based on the data provided by an industrial partner – encountering several differential sticking incidents in the recent years – stuck pipe incidents are simulated in laboratory conditions and the results are compared to the field data. Work started with creating mud samples, which resemble the field muds applied when differential sticking occurred. Then using a Fann Differential Sticking Tester apparatus, measurements were taking in order to determine the friction factor of the mud samples. The calculations of theoretical friction force values were carried out by assuming different hypothetical embedded depths and stuck pipe intervals. Finally conclusions were drawn concerning the potential field and laboratory applications of such testing procedures.

2. THE THEORY OF DIFFERENTIAL STICKING

In order to prevent differential sticking, to understand the mechanics of this phenomenon is inevitable. First of all, for differential sticking to occur, a contact between the drillstring and the damaged or poor quality filter cake has to be present. This contact can easily happen, as most boreholes have a deviation. *(Miska, Mitchell 2011).* The following contributing factors are also highly important. One of the main causes of differential sticking is the pressure difference in the wellbore, caused by the hydrostatic pressure generated by the mud column, which is greater than the formation pressure during overbalanced drilling operations. *(Drilling Fluids Engineering Manual 2006)* Hence to maintain this overbalance as low as possible is an important task in the planning phase. *(Rabia 2009)* The value of overbalance above which the risk of sticking becomes high is a function of formation characteristics, hole angle, hole size, bottom hole assembly (BHA), pipe contact area with the permeable formation, mud type and mud properties. *(Reid, Meeten, Way 2000)* Other important factor is the thickness of the filter cake deposited on a permeable formation; therefore a good quality cake is essential to avoid sticking. The amount of time while pipe does not move is also crucial, as sticking occurs most often when tripping and surveying operations take place, or during drilling when connections are made. *(Drilling Fluids Engineering Manual 2006)* A note has to be made, as field reports indicate, that on rare occasions even the pipe which moves or rotates slowly *(Reid, Meeten, Way 2000)* and even the logging tool or wireline may become differentially stuck. *(Dupriest, Elks, Ottesen 2011)* Differential sticking is indicated by no pipe movement and unchanged circulation.

2.1. Basic Concept of Differential Sticking

When drilling through a permeable formation using the conventional overbalanced method, the drilling fluid tends to flow into the permeable zone. As it happens, the fluid phase of the mud filtrates through the formation, while the solid phase is deposited on the borehole wall, building a nearly impermeable filter cake. Therefore a pressure gradient is present across the filter cake. If the drillstring contacts the mud cake and the impermeable layer is damaged, a hydraulic seal is formed and the pressure gradient now acts across the drillstring. In this case the string is differentially stuck. *(Miska, Mitchell 2011)* Figure 1 shows this basic concept of differential sticking. The pressure difference holds the pipe against the borehole wall, but the severity of sticking also depends on the embedded depth, which is a function of the thickness of the filter cake, as it determines the area of contact between the drillpipe and the mud cake. Therefore excessive drill solids and high fluid loss make it more difficult to pull the pipe free, by the means of increased friction factor and filter cake thickness. *(Drilling Fluids Engineering Manual 2007)*. The ratio of pipe-to-hole diameters also affects the initial area of pipe being embedded in the filter cake. *(Helmick, Longley 1957)* Moreover, adhesion and cohesion may also interfere with pipe movement. *(Dupriest, Elks, Ottesen 2011)*

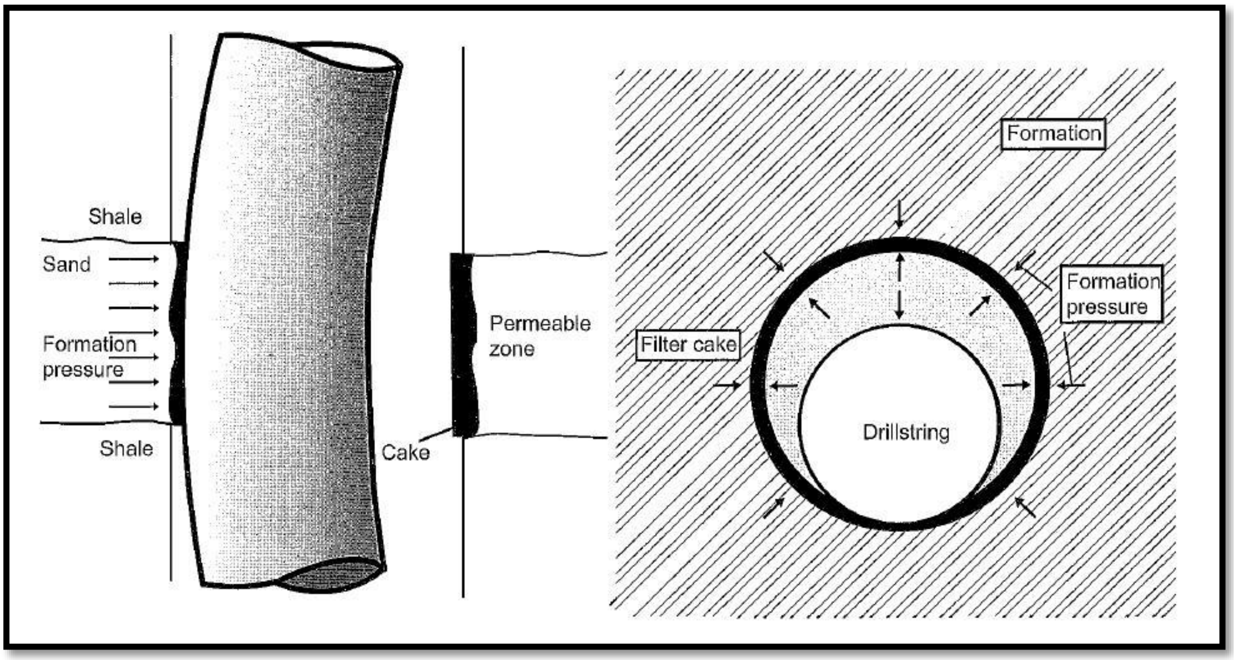


Figure 1: Basic concept of differential pressure sticking *(Miska, Mitchell 2011)*

2.2. Explanation Based on Terzaghi's Theory

Outmans (1957) has given an explanation of the mechanism of differential sticking by means of soil mechanics, based on Terzaghi's theory of clay consolidation. Terzaghi proposed a differential equation by which the hydraulic stress and the consolidation can be determined in function of time for any given point inside the examined clay formation. Outmans proposed, that the filter cake should be examined as a tiny clay formation, which loses its water content after sticking occurs. He found that the primary cause of sticking is a stationary pipe, which lies in the filter cake, while the differential pressure and the length of the time interval, until the pipe stays still determine the severity of the incident. The theory claims that any change in stress is caused by an alteration in water content. *(Outmans 1957)*

When a nearly impermeable mud cake is formed opposite a permeable layer, a certain distribution of hydraulic and effective stresses acts inside the mud cake. This is due to the inhomogeneous texture of the filter cake and the pressure difference between the mud column and the formation. Effective stress are the one, that acts from grain to grain, through the contact surfaces of the solid particles, while differential hydraulic stress is the pressure of filtrate in excess of formation pressure at a given point in the mud The time-dependent stresses may be investigated by means of Terzaghi's theory. Therefore an explanation of the qualitative changes in the contact surface between the pipe and the filter cake can be given. Also the friction force between the two surfaces may be determined with respect of sticking time, borehole dimensions and mud cake characteristics. *(Outmans 1957)*

2.2.1. Stress Distribution During Drilling

Figure 2 describes the distribution of the effective or solid stress (s) and the differential hydraulic stress (w) in the filter cake during drilling. P_d, p_m and p_f indicate the differential pressure, the hydrostatic pressure of the mud and the formation pressure respectively. *(Outmans 1957)*

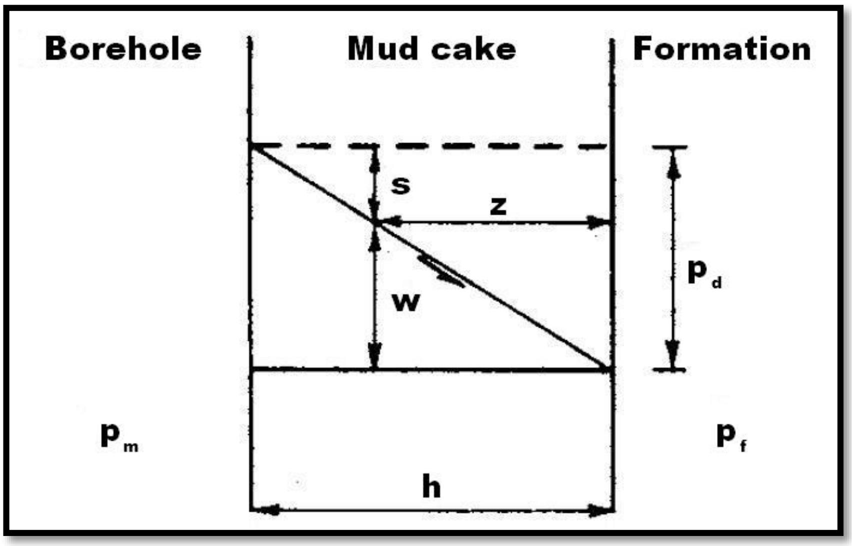


Figure 2: The distribution of the effective stress (s) and the differential hydraulic stress (w) in the filter cake during drilling *(Outmans 1957)*

The ratio p_d/h is the differential hydraulic pressure gradient inside the mud cake. If w indicates the differential hydraulic stress, it can be written as below.

$$w = \frac{p_d}{h} \cdot z \qquad (2.1)$$

Where:

w: differential hydraulic stress [kPa]

p_d: differential pressure [kPa]
h: filter cake thickness [mm]
z: distance between a given point inside mud cake and the formation [mm] *(Outmans 1957)*

As only a part of the total p_d is transmitted by w, the remaining stress must be transferred from one solid particle to the next by direct contact. This is the solid or effective stress that can be computed as follows.

$$s = p_d - w = \frac{p_d}{h} \cdot (h - z) \tag{2.2}$$

Where:
s: solid stress [kPa]
w: differential hydraulic stress [kPa]
p_d: differential pressure [kPa]
h: filter cake thickness [mm]
z: distance between a given point inside mud cake and the formation [mm] *(Outmans 1957)*

Thus w decreases linearly from p_d at the transition between the mud and the cake to zero at the contact face between the cake and the formation. Meanwhile s increases from zero at the filter cake interface to p_d at the formation. *(Outmans 1957)*

2.2.2. Stress Distribution When Drilling Is Interrupted

Both stopping circulation and pipe movement have a significant effect on the stress distribution in the mud cake. When circulation stops, the differential pressure declines till it reaches its static value. *(Outmans 1957)*

As the pipe becomes stationary, and the pipe lies in the filter cake, lubrication on the contact surface of the pipe and the cake is ceased, because the previously existing dynamic contact turned to static. After the water content of the lubricating film has seeped into the cake, filtration into the contact area stops absolutely. As long as circulation continues, the differential pressure acting on the mud cake is unchanged, though this pressure is now exerted by the pipe instead of the mud. The water content of the cake decreases steadily and also the hydraulic stress declines inside the cake until it is equal to the formation pressure. *(Outmans 1957)*

Figure 3 shows the effect of the cessation of pipe movement. Curves 2, 3, 4, 5 represent the change in w as pipe movement has been stopped and time goes by. S increases by the same increment as w decreases. This gradual conversion from w to s at the surface of the filter cake causes the friction acting on the contact face of the pipe and the cake and generates the essence of the differential sticking mechanism. This figure also demonstrates that s is always smaller at the isolated surface than inside the filter cake. Mainly this phenomenon contributes to the fact, that shearing by the pullout force would usually take place among the surface of contact and not in the cake, as the coefficient of friction between the cake particles usually would be higher compared to the one between pipe and cake. *(Outmans 1957)*

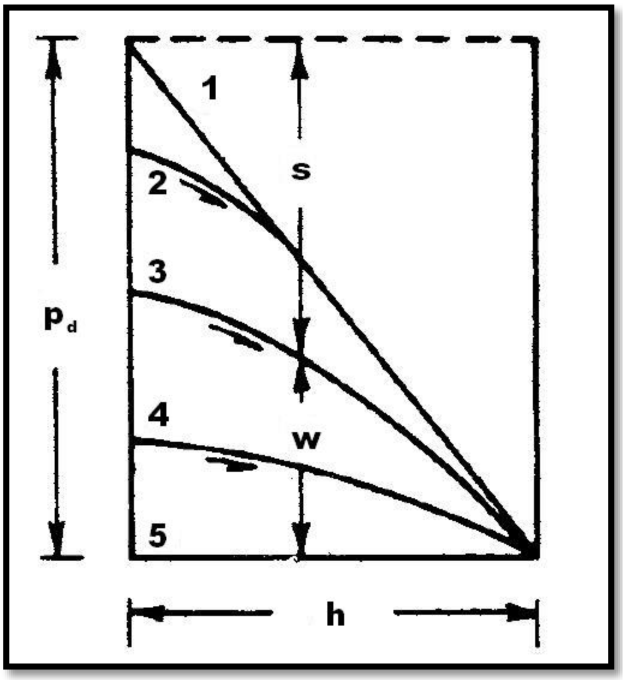


Figure 3: Successive stages of stress distribution in the mud cake during sticking *(Outmans 1957)*

The decreased water content in the mud is followed by a shrinkage process, as the porosity is reduced. While the cake shrinks, the contact area expands and new parts of the pipe become stuck, thus the friction force is increased. *(Outmans 1957)*

2.2.3. The Basic Equation for Friction Force

The friction force between the pipe and the mud cake can be computed as follows.

$$F = A_c \cdot p_d \cdot f \qquad (2.3)$$

Where:

F: friction force [kN]

A_c: total contact area [m^2]

p_d: differential pressure [kPa]

f: friction factor between pipe and cake [-] *(Outmans 1957)*

Applying the differential hydraulic stress and solid stress, the formula may also be written as below.

$$F = A_c \cdot (w \cdot f_w + s \cdot f) \tag{2.4}$$

Where:

F: friction force [kN]

A_c: total contact area [m^2]

s: solid stress [kPa]

w: differential hydraulic stress [kPa]

f_w: friction factor between steel and water [-]

f: friction factor between steel and cake [-] *(Outmans 1957)*

During drilling the solid stress at the surface of the filter cake is zero, therefore the friction force is as follows.

$$F = A_c \cdot \left(p_d + p_p\right) \cdot f_w \tag{2.5}$$

Where:

F: friction force [kN]

A_c: total contact area [m^2]

p_d: differential pressure [kPa]

f_w: friction factor between steel and water [-]

p_p: pressure exerted by pipe normal to the wall [Pa] *(Outmans 1957)*

When pipe movement stops, the solid stress starts to increase, until it equals the differential pressure. As f_w is negligible compared to f, and the total contact area can be expressed as $A = l \cdot d \cdot \alpha_c$, the friction force finally can be written as follows.

$$F = f \cdot l \cdot d \cdot s_1 \cdot \alpha_i + f \cdot l \cdot d \cdot s_2 \cdot (\alpha_c - \alpha_i) \tag{2.6}$$

Where:

F: friction force [kN]

f: friction factor between steel and cake [-]

l: length of stuck pipe [m]

d: outer diameter of stuck pipe [m]

s_1: solid stress in the initial area [kPa]

s_2: solid stress in the shrinkage area [kPa]

α_i: initial angle of contact between pipe and cake [°]

α_c: final angle of contact between pipe and cake [°] *(Outmans 1957)*

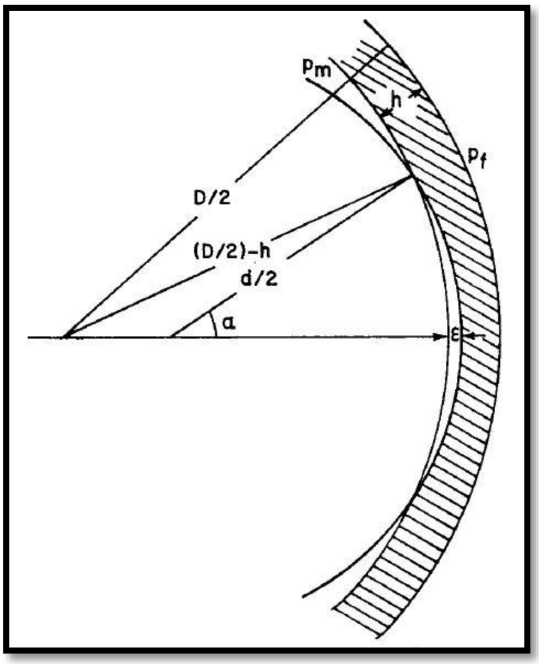


Figure 4: Contact area between pipe and filter cake *(Outmans 1957)*

As Figure 4 demonstrates, the angle of contact is measured between the points of maximum (ε) and minimum deformation of the mud cake. *(Outmans 1957)*

3. STUCK PIPE AVOIDANCE PRACTICES

As differential sticking became a major concern in the drilling industry, the first objective was to eliminate it at all. After the mechanism of sticking process was better understood, this objective shifted towards a design principle. This aims that pullout force, which can be exerted by the rig to the pipe without overcoming the tensile strength of the drillpipe, always exceeds sticking force. *(Dupriest, Elks, Ottesen 2011)*

In order to reduce the likelihood of differential sticking, it is important to determine the drilling parameters, which could be changed in order to avoid sticking. As rock formations are defined by the regional geology, while high overbalance pressures often essential for primary well control and wellbore stability, the most easily changeable parameters are the drilling fluid properties and the drillstring. *(Bushnell-Watson, Panesar 1991)*

3.1. Cake Morphology and Fluid Design

The need to optimize mud properties is of the utmost importance, as several mud variables are known to have an effect on differential sticking. These are the following:

- mud density,
- mud solids content (both high and low-gravity solids),
- generic mud type,
- specific mud additives (lubricants, bridging particles, etc.),
- fluid loss,
- filter cake quality; which includes cake thickness, cake lubricity and cake strength. *(Reid, Meeten, Way 2000)*

Of course the variables listed above are dependent from each other, so they cannot be changed separately. As some authors claim, the most important factor is the filter cake quality, which is a complex property of the mud and is a function of all the above mentioned variables. *(Reid, Meeten, Way 2000)* As the primary focus of this thesis is the effects of the mud parameters on differential sticking, this topic will be discussed in details later in Chapter 5.

3.2. Reducing Overbalance

As differential pressure is reduced, the effective stress in the contact area and the shear strength of the filter cake also decrease, therefore lower pullout force is required to free the pipe. Although reducing the mud density is an option to avoid differential sticking, it is more practical to reduce the contact area, which process also bears significantly lower risk compared to drilling with lower mud density. *(Dupriest, Elks, Ottesen 2011)*

3.3. Drillstring Design Principles

Another important factor is the effective contact area between the pipe and the permeable zone, minimizing the contact area could also decrease the likelihood of differential sticking. Drill collars (DC) are used to prevent buckling and to provide the required weight on bit (WOB), but they are prone to sticking as using them results in high pipe-to-hole diameters ratio, while their outside diameter is uniform through their entire length, so they make contact along 30 ft. *(Dupriest, Elks, Ottesen 2011)* Twisted non-circular DCs have less tendency for sticking, though they offer still a significant contact area. *(Outmans 1957)* The WOB could also be delivered by using heavyweight drillpipes (HWDP) instead of large diameter DCs, whenever it is possible and the risk of differential sticking is high. By using HWDP to apply WOB a significant reduction in the contact area can be reached. Figure 5 shows the upset contact areas of typical joints in 5 in drillpipe vs. 5 in HWDP. Therefore the area of contact could be reduced from 30 ft with DCs to 6 ft with HWDP per joint. Though HWDPs are not as stiff and their weight per foot is less compared to DCs, for most applications they could apply enough WOB and also prevent buckling. As operators began to replace DCs with HWDP in directional and vertical wells, the numbers of stuck pipe incidents decreased immediately in the mid 1990s. *(Dupriest, Elks, Ottesen 2011)*

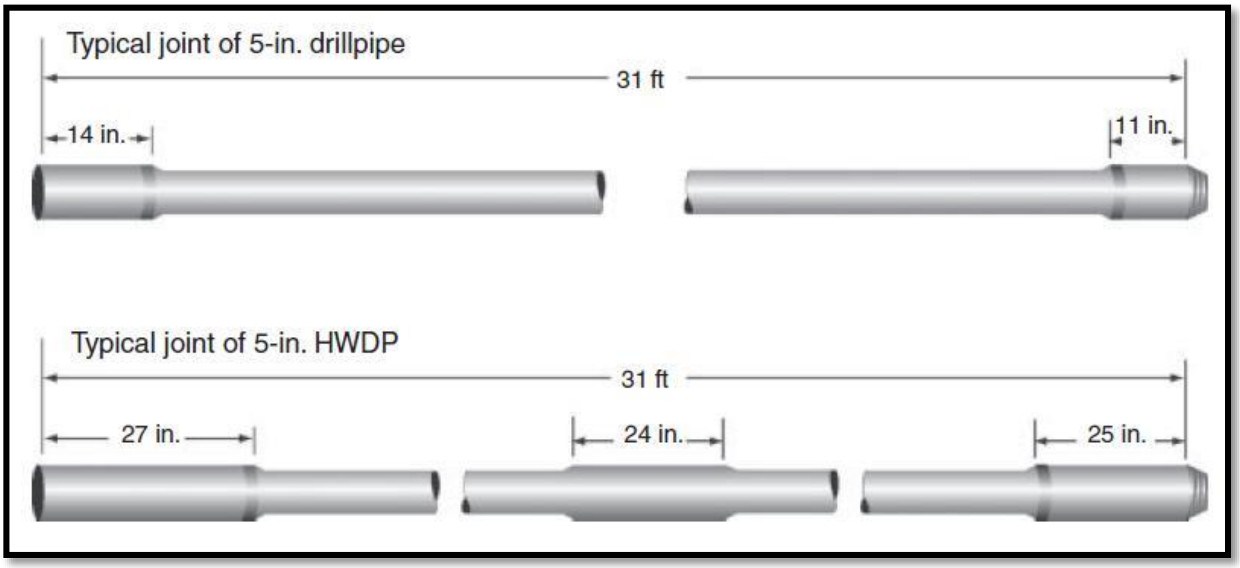


Figure 5: Comparison of upset contact areas in DP and HWDP *(Dupriest, Elks, Ottesen 2011)*

It is also essential to avoid slick assemblies whenever the sticking is a real threat. Using fully stabilized bottom hole assembly ensures that there is no wall contact between DCs and the formation. *(Dupriest, Elks, Ottesen 2011)*

Eliminating HWDP at higher angles and extended reach sections and using conventional drillpipes (DP) provides significantly less contact area. At low angles DP can be used only to a limited extent due to its tendency of buckling at low forces, but as buckling is suppressed at high angles, a significant amount of compression can be delivered by DPs. Due to this the contact area is reduced from 6 ft with HWDP to less than 3 ft with DP per joint (Figure 5), which becomes important when traversing permeable layers at high angles.

As previously mentioned, DCs have the highest pipe-to-hole diameters ratio, supposedly stuck point should be found in the BHA. Occasionally field cases report differentially sticking which occurs above the BHA in the DP section. Examining these anomalies the presence of wear grooves were identified. High resolution, 3D borehole images made in high-angle wells show the development of a groove in the bottom section, which is created by the rotation of the tool joints or tube body of the DP (Figure 6). This curvature contributes to an increase in contact area between the pipe and the formation, therefore the required pullout force also rises. The groove cannot be eliminated, but its effect could be minimized by using DPs instead of HWDPs at high angles and reducing the vertical load on the bottom of the hole.

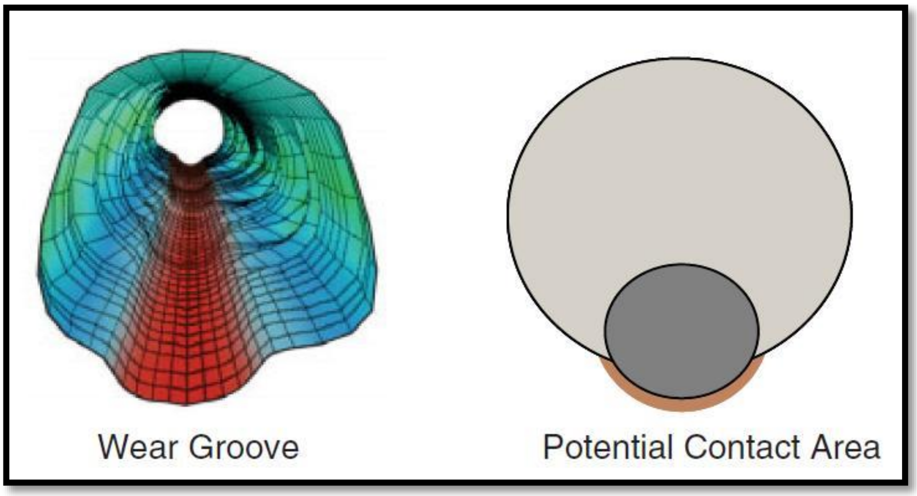


Figure 6: Wear groove and the increased contact area *(Dupriest, Elks, Ottesen 2011)*

When applying a jar in the drillstring, another sticking factor has to be considered. Though the use of a drilling jar gives tremendous help during freeing procedures, in terms of differential sticking potential it represents the same risk as DCs. Using standoff subs (Figure 7) when a drilling jar is present in the drillstring could prevent the jar contacting the formation, therefore sticking may be avoided.

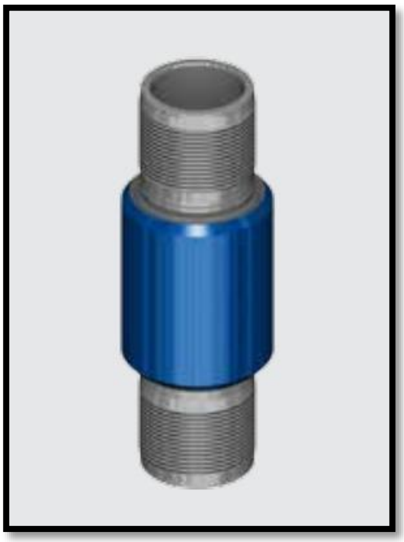


Figure 7: Standoff sub reduces contact with borehole walls *(www.schlumberger.com)*

3.4. Minimizing Still-Pipe Time

As it was already described, the filter cake has little shear strength until its internal pressure declines and fluid is lost, thus high pullout resistance cannot occur instantly. The actual shear strength development with respect to time depends on many factors, so it cannot be predicted. To address this problem, the industry developed a real-time surveillance process. The so-called progressive sticking test is conducted before making a connection, whenever the risk is thought to be high. During the test, the pipe remains still for a predetermined, short period of time, and then the pullout force is measured. The still-pipe time is increased progressively until the time interval which is required to make a connection is reached. If the maximum pullout force remains below a safe margin, the connection can be made. Otherwise well conditioning may be required, or mud density should be reduced when applicable. The progressive sticking test is usually carried out when traversing long permeable sections, or if wear groove is believed to be present. *(Dupriest, Elks, Ottesen 2011)*

3.5. Cake Remediation During Drilling

An important role of stabilizers in cake remediation has to be mentioned. The distribution of solids in the cake that is formed instantaneously at the bit is a function of drill rate and mud density. In case of a light fluid and high drill rate, the initial cake will mostly consist of drill solids, whereas with high density mud and low drill rate it will largely made up of weighting solids (barite). When stabilizers are present, they will shear the initial cake as rotating and much of this poor quality cake will be removed. The exposed surface of the cake will capture only those particles that fit within the texture of the cake, the larger ones will be removed by fluid shear. As stabilizers shear the cake over and over, the re-exposed surface captures progressively finer solids, thus the permeability of the filter cake decreases. This process results in finer blocking solids at the surface so the remaining gaps can be sealed more easily by fluid loss control material. *(Dupriest, Elks, Ottesen 2011)*

4. METHODS AND PROCEDURES FOR FREEING STUCK PIPE

4.1. Freeing Stuck Pipe Mechanically

Jarring is the process, when a large force impulse is used to impact the stuck part of the drillstring. Drilling jars can operate on hydraulic or mechanical principle. Up and down hit can be achieved with most jars, though they are designed to impart a larger impact force upward. *(Miska, Mitchell 2011)*

When the pipe is differentially stuck, jarring is the most effective method in order to free the pipe. While operating the drilling jar, additional torque should be used for maximum efficiency. This action has to be started as soon as possible after the pipe became stuck, because the likelihood of successfully freeing the pipe diminishes with time, as the contact area between the pipe and mud cake increases. *(Drilling Fluids Engineering Manual 2007)* Generally, if jarring process is ineffective within the first few hours, jarring should be terminated. The only exception is when large volumes of spotting fluids are displaced in the annulus at the stuck zone. *(Miska, Mitchell 2011)*

4.2. Freeing Stuck Pipe with Spotting Fluids

In most cases some type of spotting fluid is getting mixed while jarring is to be continued. If the initial jarring cannot free the pipe, the drilling mud in the annulus at the stuck point has to be displaced by a different fluid, which technique is referred to as spotting. Spotting fluids contribute to the freeing process by lubricating the pipe-cake contact area. To do so, determining the depth of the stuck zone is a crucial task. Surveys can be run, but such operations take a significant amount of time. The pipe-stretch method is a fast and easily feasible way to determine the stuck point, and its accuracy is appropriate in most vertical wells, when a few m^3 of drilling fluid is spotted. The pipe-stretch method is based on applying overpull on the stuck pipe and measuring the pipe-stretch with different loads on the derrick. *(Drilling Fluids Engineering Manual 2007)*

A common cause of unsuccessful freeing procedures is the insufficient volumes of spotting fluids. As pipe stays stationary, higher pipe sections often become stuck. Field practice suggests spotting enough fluid to reach all exposed permeable zones, with a volume left in the drillpipe to create annular movement at predetermined time intervals. After spotting, time is required before the pipe can be released; this amount of time depends on the mud properties, mud-displacement efficiencies, pipe-to-hole geometry and differential pressure.

As obtained from field data, an average of eight to ten hours is required for release. *(Miska, Mitchell 2011)*

Figure 8: Cracking effect of filter cike using oil only (left) and Pipe-Lax-oil mixture (right) *(Drilling Fluids Engineering Manual 2007)*

In case of water-based muds, oil-based spotting fluids are preferred. When environmental issues are present, alternative solutions should be used. Unweighted and weighted spotting fluid formulas are available as well. Though using diesel oil alone lead to success in some cases, the invention was done to use additives mixed with diesel oil, which contributed to higher probability of freeing the pipe. A frequently used product in Hungary is Pipe-Lax by MI-SWACO, which alters the contact area between the pipe and the filter cake by cracking the cake (Figure 8). Therefore the lubricating mixture can pass through the mud cake more rapidly, leading to shorter period of stuck-time. Pipe-Lax consists of gellants, emulsifiers, wetting agents and filter cake cracking materials. *(Drilling Fluids Engineering Manual 2007)*

4.3. Freeing Stuck Pipe by Reducing Differential Pressure

Stuck pipe also could be freed by means of decreasing differential pressure, which can be accomplished in several ways.

4.3.1. Spotting Reduced Density Fluids

Spotting a lighter fluid also leads to the reduction of differential pressure; oil and water are widely used to achieve this goal. Well control issues are primary concerns during these procedures, so caution should always be exercised in order to prevent the well kicking. *(Drilling Fluids Engineering Manual 2007)*

4.3.2. Applying Drill Stem Test Tools

Using a Drill Stem Test Tool is a safe way to reduce differential pressure, though this method is quite time consuming, as it is necessary to back off, run a caliper log to select a near-gauge zone for setting the packer, make a conditioning trip and mobilize DST equipment. The process is as follows. A fishing assembly has to be run with the DST string filled with a lower density fluid. After the fishing assembly is attached to the fish, the packer is set, hence reducing the hydrostatic pressure, which also leads to a decrease in the differential pressure. In case of the fish comes free, the packer should be released then the pipe needs to be moved up and down, preventing differential sticking to occur again. *(Drilling Fluids Engineering Manual 2007)*

4.3.3. U-Tube Technique

The U-Tube technique refers to the process when differential pressure is decreased by reducing the height of the mud column in the annulus below the bell nipple. First, light fluid (water, oil) or gas (nitrogen) is pumped down in the drillstring, then the pressure with some fluid is bled off the standpipe. Therefore the heavier mud in the annulus is allowed to 'U-Tube' back into the drillstring, reducing the hydrostatic pressure in the annulus. The exact volume of the lighter fluid should be carefully calculated. Caution also has to be made not to plug the bit, hence this procedure should not be performed with small nozzle bits. Before attempting this technique, formation pressures and possible productive zones have to be considered. *(Drilling Fluids Engineering Manual 2007)*

5. DRILLING FLUIDS DESIGN

5.1. Basic Concepts of Drilling Fluids Engineering

Drilling fluids or muds have an essential role in the success of the rotary drilling process. The majority of the drilling problems are also related in some ways to the drilling fluid. To select the proper mud for a particular well, the following aspects have to be considered:

- the rock characteristics and the properties of the formations to be drilled,
- the source and quality of the water to be used as the continuous phase of the mud,
- the ecological and environmental considerations. *(Miska, Mitchell 2011)*

The most common classification of drilling fluids is based on their continuous phase, so we can define:

- water-based fluids (WBF),
- oil-based (OBF) and synthetic-based fluids (SBF),
- pneumatic (gas) fluids. *(Miska, Mitchell 2011)*

To set, maintain and control the required parameters of the mud, various additives are used for drilling muds. As this thesis deals with the testing of WBFs, the topic of OBF/SBF/pneumatic fluid additives will not be covered. The additives can be liquid or solid, solids can be either active or inactive. Active solids react with the water phase, while inactive solids stay in inert state. Additives may be classified as follows:

- weighting agents,
- fluid loss control additives,
- thinners or dispersants,
- lost circulation materials,
- surfactants,
- other additives. *(Miska, Mitchell 2011)*

The most important weighting agent in the drilling industry is barite, with a density of 4.2 g/cm^3. Adding barite to the base fluid, drilling fluids with densities from 1.08 to 2.28 kg/l can be produced. Other minerals for weighting are calcium carbonate (2.7 g/cm$^{3)}$, siderite (3.08 g/cm^3), ilmetite (4.6 g/cm^3), hematite (5.05 g/cm^3) and galena (7.5 g/cm^3). Fluid loss control additives, like clays and polymers are widely used to prevent or minimize the filtration of water into the formation by sealing the permeable zone with a thin, nearly impermeable filter cake. The main functions of thinners and dispersants are reducing flow resistance and gel development, but they also contribute to the improvement of fluid loss control. To prevent lost circulation, fibrous materials (wood fiber, paper pulp, etc.), granular materials (nutshell, calcium carbonate, etc.) and flake like materials (mica flakes, etc.) are widely used. They can work as bridging particles in highly permeable formations with large pore throats. Surface active agents are soluble compounds that help to reduce the surface friction force between two different materials by concentrating on the surface boundary. The surfactants have a specific molecular structure with different groups having hydrophobic and hydrophilic solubility properties. These agents are widely used to change the colloidal state of clay minerals and polymers from dispersion to flocculation. Other additives may added for pH control, inhibition control, corrosion mitigation, lubrication, moreover to kill bacteria in starch-content muds, reduce different contaminations and free stuck pipe. *(Miska, Mitchell 2011)*

5.2. Design Principles to Avoid Differential Sticking

5.2.1. Effect of Mud Type

Though the sticking potential varies greatly within a mud type, depending on the precise formula, the generic mud type determines the sticking tendency of a certain drilling fluid. Figure 9 shows the release torque for two WBFs and one OBF, as measured in laboratory conditions.

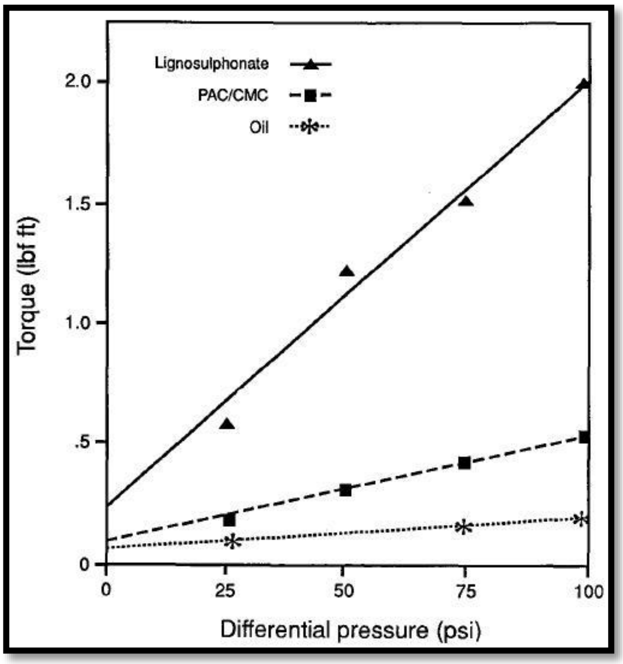


Figure 9: Effect of mud type on differential sticking (*Bushnell-Watson, Panesar 1991)*

Generally, OBFs tend to stick the less, while clay WBFs are prone to contribute to sticking at a higher degree. Polymer WBFs fall between these two categories. *(Reid, Meeten, Way 2000)* Environmental legislations and other technical or financial factors often limit the use of OBFs, therefore the differential sticking requirements are not the primary concerns in most drilling fluid selection procedures. *(Bushnell-Watson, Panesar 1991)*

5.2.2. Effect of Fluid Loss

Generally, as fluid loss is reduced, the probability of differential sticking is decreased as well, though not all studies show a straightforward correlation between API fluid loss and differential sticking tendency. Table 1 describes the API fluid loss values and cake thickness of five different drilling fluids, tested in laboratory. It is obvious, there is no strict relationship between API fluid loss, cake thickness and release torque. PAC/CMC/CMHEC refers to polyanionic-cellulose, carboxymethyl-cellulose and carboxymethyl-hydroxyethyl-cellulose respectively. *(Bushnell-Watson, Panesar 1991)*

Mud type	Release torque [lbf/ft]	Cake thickness [mm]	API fluid loss [ml/30 min]
Lignosulphonate	2.10	1.6	23
Gypsum	0.91	2.4	34
PAC/CMC	0.52	1.2	6
CMHEC	0.41	1.6	7

Table 1: Relationship between API fluid loss, cake thickness and release torque *(Bushnell-Watson, Panesar 1991)*

Another study *(Bushnell-Watson, Panesar 1991)* investigated the effect of the increased level of a fluid loss additive (CMC) for a PAC/CMC drilling fluid (Figure 10). Increased CMC level lead to thicker filter cake, but the release torque dropped significantly. It is thought, that the higher polymer level decreased the frictional or adhesive forces at the pipe-mud contact face, therefore compensating for the thicker mud cake. This research also supported the fact, that cake thickness alone cannot predict the sticking tendency of a mud.

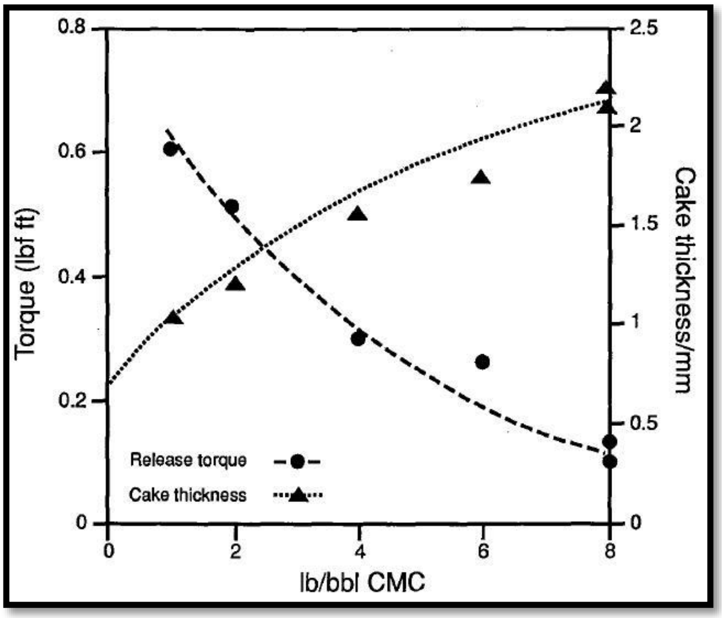


Figure 10: Effect of increasing the CMC level for a PAC/CMC mud *(Bushnell-Watson, Panesar 1991)*

The optimal filter cake also has a highly slow rate of filtrate loss from the cake to the formation to prevent high shear strength to act immediately after sticking occurs. Both filtration control and the presence of blocking solids are required for an effective filter cake. The most common blocking solid is barite, however at higher pore throats barite particles may be too small to fulfill their function and low density fluids also contain little barite. There is also a significant drawback related to barite: when reaching a potential producing zone, the barite may contaminate the formation for good, as the removal of the inert barite particles is nearly impossible. For that reason, calcium carbonate is frequently used as blocking solid, because it has the advantage of being soluble in acids.

An important note has to be made regarding the API testing protocols for fluid loss (FL). The D_{50} of the size distribution of calcium carbonate varies between 5 and 50 μm. The standard filtration paper has openings range from 1 to 2 μm. If applying this value for a sandstone formation, its permeability would be less than 5 mD. As field practice shows, the real differential sticking risk occurs in the 500 to 7,000 mD range. It means that low API standard FL values can be achieved with filtration material alone and very little blocking solids, hence the FL tests do not represent actual downhole conditions. It is advised to carry out API particle-plugging tests, where the filtration medium simulates the local permeability, moreover the applied differential pressure and temperature also reflects the downhole conditions. *(Dupriest, Elks, Ottesen 2011)*

5.2.3. Effect of Solids Level

Increased solids level is found to increase the likelihood of differential sticking. This statement applies for both weighting agents and drilled solids. Due to the presence of the latter, field muds have higher sticking tendency compared to laboratory muds. *(Bushnell-Watson, Panesar 1991)*

5.2.4. Effect of Lubricants

Adding lubricants (specific additives, diesel oil, mineral oil) to both WBF and OBF will reduce the differential sticking potential, moreover, when sticking still occurs, the force needed to free the pipe is reduced significantly as well. The mechanisms of lubricants can vary, depending on their chemical composition and solubility or dispersibility in the drilling fluid. These mechanisms are as follows:

- reducing the steel-filter cake adhesion force by coating the pipe surface,
- reducing the yield stress of the filter cake by incorporating into the mud cake. *(Reid, Mieten, Way 2000)*

A relationship can be found between drilled solids level and the effect of lubricants. As the level of drilled solids increases, higher dosage of lubricant is needed to achieve the same reduction in the required release torque. The main cause of this phenomenon is the increased surface area of the total solid content. A laboratory study describes this difference between an oil-based field mud sample and a laboratory mud sample

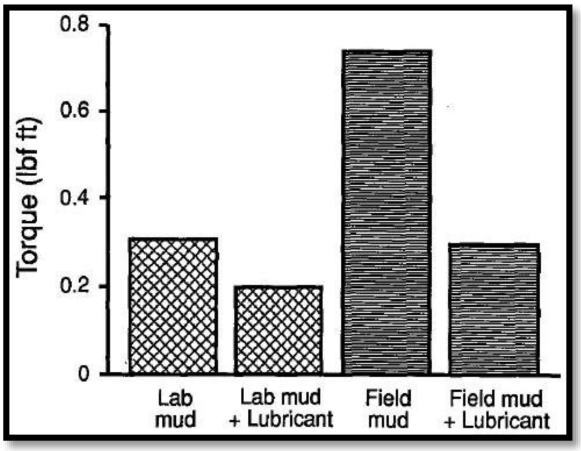


Figure 11: Effect of lubricants on different mud samples *(Bushnell-Watson, Panesar 1991)*

The lab mud had the exact same formula as the field mud, the only difference was the total absence of drilled solids. The release torque was much higher for the field mud than for the lab mud (Figure 11). It was found, that the pipe is freed at the cake-formation interface without a lubricant, whereas with lubricant the pipe is freed at the pipe-cake contact face. *(Bushnell-Watson, Panesar 1991)*

5.3. Testing of Drilling Fluids

In order to set, maintain and control the desired drilling fluid parameters during drilling operations, the proper testing of these fluids is crucial. Moreover, to choose the suitable mud for a given well, extended measurements should be implemented before rigging up to ensure that the mud will work properly, while field data obtained from offset wells should be used as well. Enhancing existing formulas and developing new fluid systems and additives are also carried out by laboratory testing. Therefore standardized methods and equipment were developed to achieve these goals. The following mud properties are tested routinely, both in laboratories and at drillsites:

- density,
- viscosity,
- filtration (fluid loss),
- sand content,
- liquid and solid content,
- hydrogen ion concentration (pH),
- chemical analysis (alkalinity, carbonate-, chloride-, calcium-, sulfate-, potassium-glycol- and polymer-concentration, total hardness, corrosive substances, etc.)
- resistivity. *(Drilling Fluids Engineering Manual 2007)*

When differential sticking risk is present in the borehole, an instrument which simulates the sticking process may also be used to determine the sticking tendency of the drilling fluid. *(Reid, Mieten, Way 2000)*

The field testing procedures for WBFs are standardized by American Petroleum Institute (API), as written in API Recommended Practice 13B-1. Measuring density, viscosity, fluid loss and sticking tendency is of the utmost importance of this thesis, hence the principles of these testing methods should be examined in details.

5.3.1. Testing Density

Drilling fluid density or mud weight (MW) can be accurately measured with the use of a mud balance (Figure 12). The mud balance is a simple instrument, which consists of a base with a knife edge holder and level vial, a graduated arm with sample cup, lid, knife edge and counterweight. When testing, the arm rests on the knife edge holder and it can be balanced by moving the counterweight along the arm. The cup is completely filled with mud, which can be achieved by expelling some fluids through the hole placed on the top of the lid. *(Drilling Fluids Engineering Manual 2007)* MW can be read at the indicated edge of the counterweight in lb/gal (ppg) or kg/l (SG/specific gravity). If necessary, mud gradient may be calculated as follows:

$$Mud\ gradient\ [psi/ft] = MW\ [ppg] \cdot 0.052 \tag{5.1}$$

$$Mud\ gradient\ [bar/m] = MW\ [SG] \cdot 0.0981 \tag{5.2}$$

In case of gas or air bubble entrapments in the sample fluid, a specially designed cup – which can be pressurized – should be used in order to decrease the gas phase to a negligible volume. *(Fann 2015)*

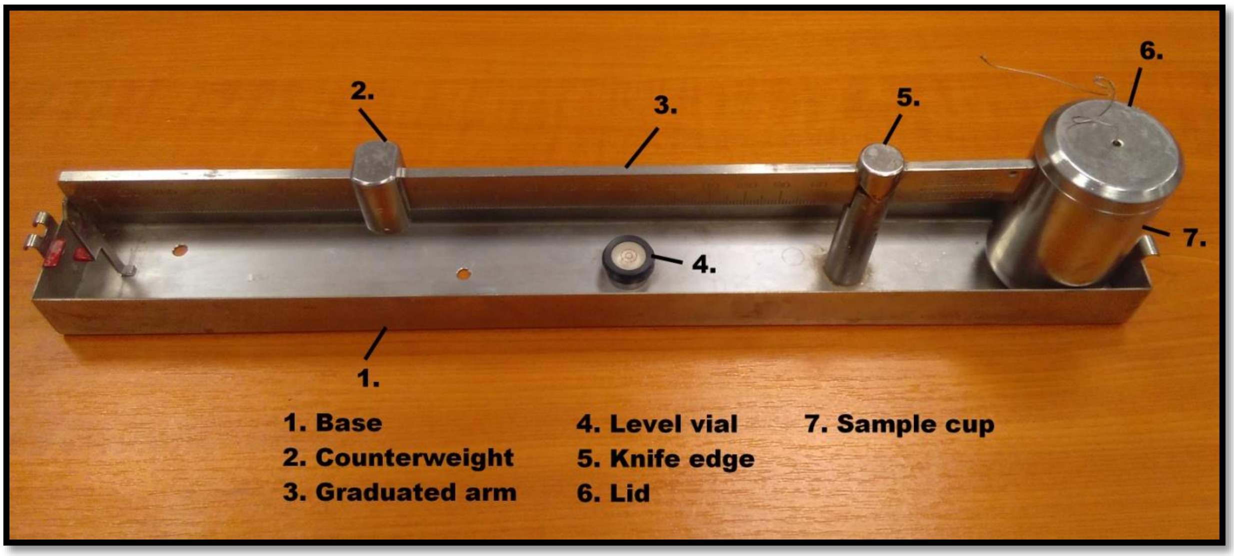


Figure 12: Mud balance

5.3.2. Testing Rheology

The industry standard instrument for viscosity testing is the Fann Model 35 viscometer, which is a Couette-type coaxial cylinder rotational viscometer, recommended for testing Bingham plastic fluids (Figure 13). The Couette-type refers to the operational principle, which means that the outer cylinder, often called rotor is rotating while the inner cylinder, also known as bob is stationary. *(Fann 2013)*

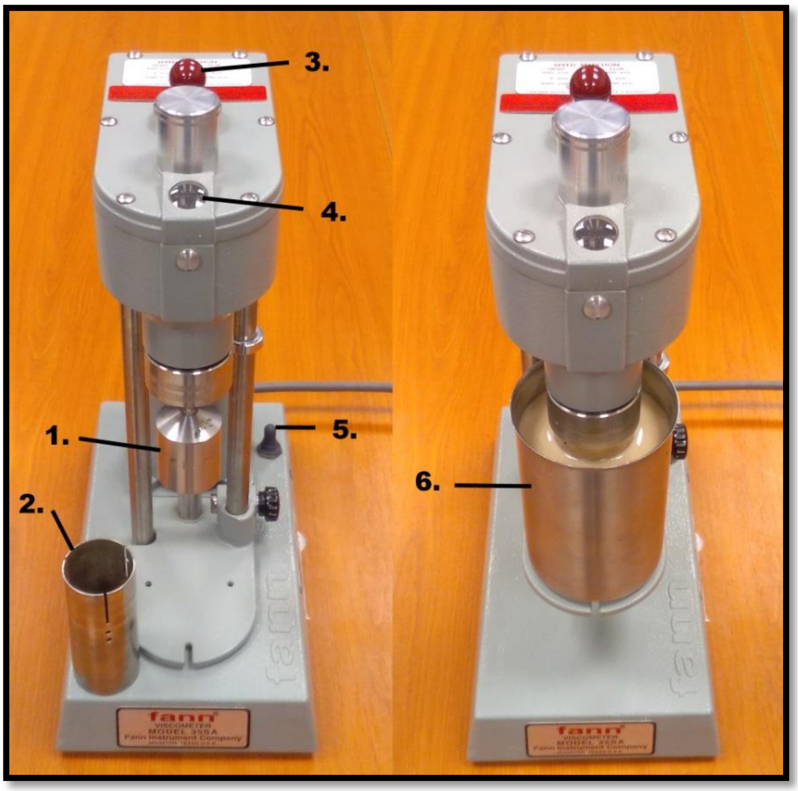


Figure 13: Fann Model 35 Viscometer, Parts: 1. Bob, 2. Rotor, 3. Gear shift knob, 4. Dial, 5. Motor speed switch, 6. Sample cup *(Fann 2013)*

During testing, the fluid sample is placed in a sample cup, then the cylinders are immersed in the fluid, therefore mud sample is contained in the annular space between the two cylinders. As the rotor starts to rotate at known velocities, a movement is generated in the fluid sample as well, which generates a torque on the bob. The displacement of the inner cylinder is proportional to the torque acting on its surface. A torsion spring restrains the movement of the bob, and the torque can be read at the dial attached to the bob. *(Drilling Fluids Engineering Manual 2007)* The torque is equivalent to the shear stress acting in the fluid and the dial reading unit is 'Fann', which can be converted to lb/100 ft^2 by using the following correlation. *(Fann 2013)*

$$1\ Fann = 1.065\ lb/100\ ft^2 \tag{5.3}$$

At drillsite tests the above mentioned conversion is neglected, the direct dial readings are recorded for practical purposes.

The Model 35 can obtain speeds of 600, 300, 200, 100, 6 and 3 Revolutions per Minute (RPM), so different flow patterns may be simulated. The API standard drilling fluid viscosity test consists of recording the 600, 300, 200, 100, 6 and 3 RPM dial readings and 10 sec (initial) and 10 min gel strengths at 120 °F (~49 °C). *(Drilling Fluids Engineering Manual 2007)* Using the parameters just mentioned plastic viscosity (PV) and yield point (YP) can be calculated.

Measuring the gel strength is as follows.

- stirring the sample at 600 RPM for 15 sec,
- switching the gear to 3 RPM and stopping the motor immediately,
- waiting for the pre-determined time (10 sec or 10 min),
- starting the motor at 3 RPM and recording the maximum dial reading as 10 sec or 10 min gel strength *(Drilling Fluids Engineering Manual 2007)*

Plastic viscosity and yield point can be calculated as given below.

$$PV = \theta 600 - \theta 300 \tag{5.4}$$

Where:

PV: plastic viscosity [cP]

θ600: dial reading at 600 RPM [Fann]

θ300: dial reading at 300 RPM [Fann] *(Fann 2013)*

$$YP = 2 \cdot \theta 300 - \theta 600 = \theta 300 - PV \tag{5.5}$$

Where:

PV: yield point [lb/100 ft^2]

θ600: dial reading at 600 RPM [Fann]

θ300: dial reading at 300 RPM [Fann] *(Fann 2013)*

These calculations assume Bingham plastic fluids, in this case the flow curve is a straight line. (Figure 14) Plastic viscosity indicates the slope of the line between the two dial readings, while yield point stands for a theoretical point, at which the straight line intercepts the vertical axis. *(Fann 2013)*

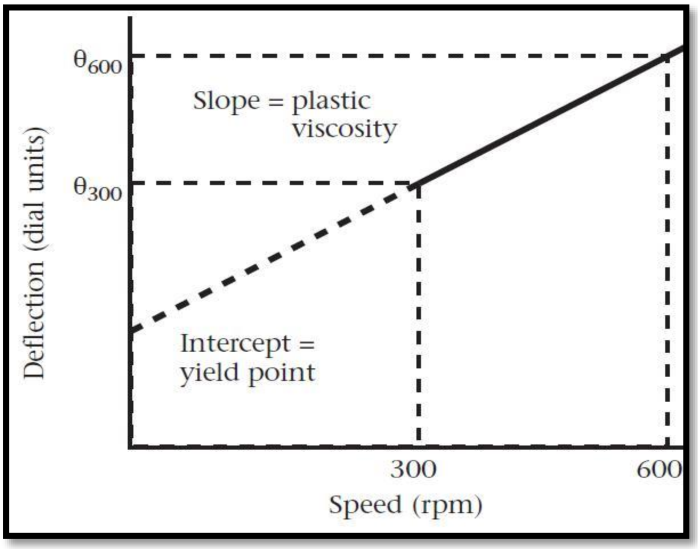


Figure 14: Flow curve for a Bingham plastic mud *(Drilling Fluids Engineering Manual 2007)*

5.3.3. Testing Filtration

Filtration test simulates the process when filter cake is deposited on the borehole wall due to the differential pressure. So fluid loss and cake thickness can be determined; and filter cake quality can be examined to some extent. The API FL test is carried out at surface temperature at 100 psi (6.9 bar) for 30 min, the fluid loss is recorded in ml, while cake thickness is measured in $^{1}/_{32}$ inch. The API standard instrument for filtration test is the filter press, a multiple-unit instrument were used for this thesis (Figure 15).

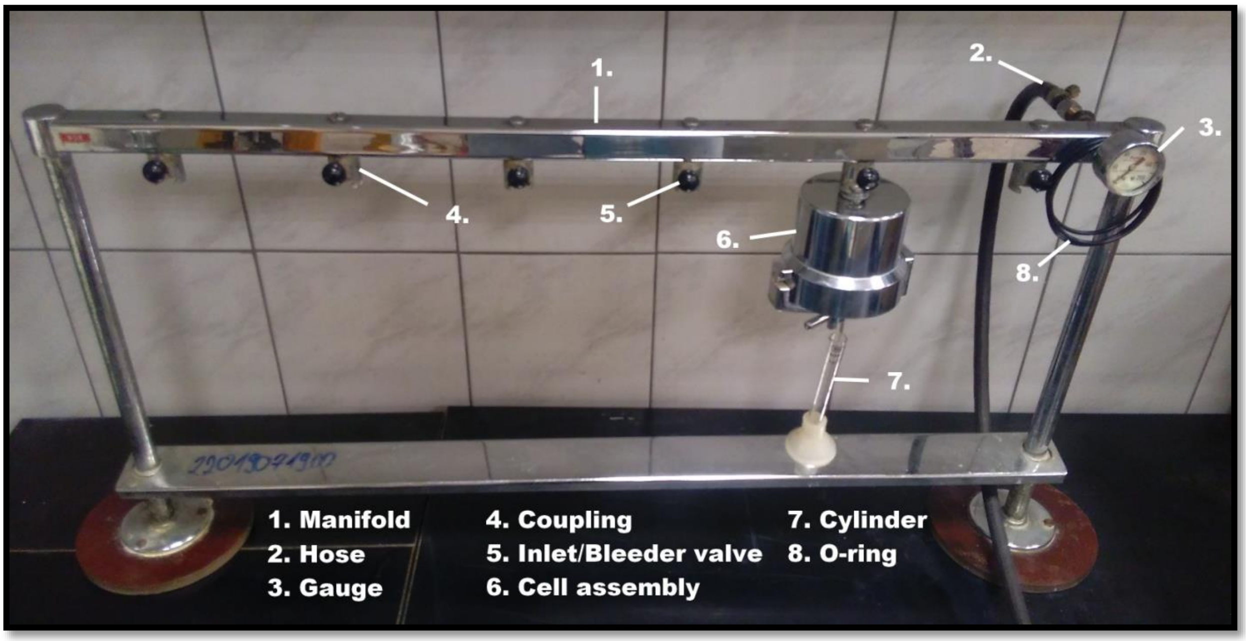
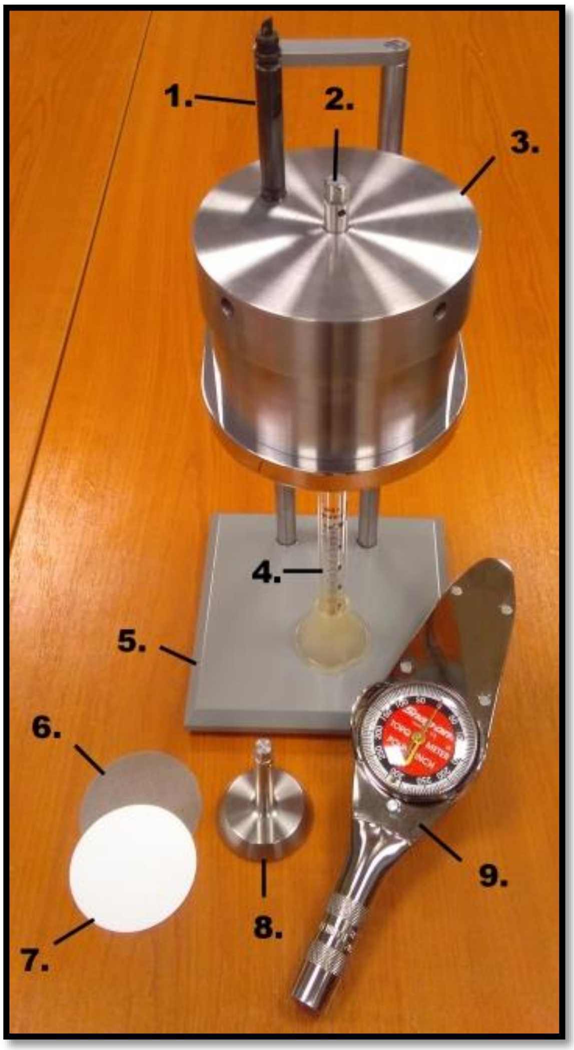


Figure 15: Multiple-unit filter press

It consists of a manifold, pressure regulator, hose, inlet/bleeder valves, gauge and cell assemblies. External pressure source, such as nitrogen or carbon-dioxide is also required. The cell assembly consists of a cell and a lid equipped with a screen. The cell has an O-ring groove to prevent the pressure bleeding off, and a small opening in the bottom part to expel filtrate. When testing, the cell is filled with mud sample to within $^1/_4$ inch of the O-ring groove, then the filter paper is placed on top of the O-ring. After the cell is closed, it is turned over and inserted into the coupling located in the manifold. A graduated cylinder is used to collect the filtrate. When the inlet valve is opened, pressure applies to the cell, hence filter cake starts to build-up and filtrate is slowly passing through the cell opening. After 30 minutes, the pressure is bled off, the cell is disassembled; and the fluid loss and cake thickness is recorded. *(Drilling Fluids Engineering Manual 2007)*

5.3.4. Testing Differential Sticking Tendency



Several instruments have been developed to determine the sticking tendency of drilling fluids. These instruments may differ in arrangement and applicable temperature and pressure ranges, but they all simulate the pipe-wellbore geometry and filter cake building process. The purpose of these tests is to determine the required release torque or pullout force. A Fann Model 21150 Differential Sticking Tester (DST) was used for the measurements of this thesis (Figure 16).

Figure 16: Fann Differential Sticking Tester *(Fann 2010)* Parts: 1. Valve stem, 2. Plate stem, 3. Cell assembly, 4. Graduated cylinder, 5. Stand, 6. Locking mesh disc, 7. Filter paper, 8. Torque plate, 9. Torque wrench

The Model 21150 is basically a modified filter press fitted with a steel plate, which is pressed down in the filter cake during testing, therefore simulating the differential sticking process. After a pre-determined time, a torque wrench is attached to the plate stem, and the release torque can be recorded. *(Fann 2010)* Hence the friction factor between the filter cake and steel can be calculated, and the likelihood of a stuck pipe incident for a given fluid may be estimated. The effects of drilling fluid treatments and spotting fluids can be investigated as well. The friction factor depends on the filter cake quality, which is a complex property of the mud and is a function of several variables, as written in Chapter 3.1. The exact calculation method to determine the friction factor will be examined in details in Chapter 6.2.

6. SIMULATING STUCK PIPE INCIDENTS

A well-known Hungarian company provided data for this thesis. The operator encountered several differential sticking incidents in the recent years. The purpose of this work was the following: trying to repeat the stuck pipe events in laboratory using as much field data and simulate the borehole conditions as accurate as possible. The source of information was the collections of drilling daily reports of three exploration wells. In case of the second well, two stuck pipe incidents occurred. The lack of other information (i.e. mud logs, well plan) meant that some parameters could not be calculated, in these cases estimations and correlations were used to determine the required data. The steps of the research process were as follows:

- Mixing mud samples that resemble the field muds used when differential sticking occurred.
- Taking measurements using a Differential Sticking Tester to determine the sticking tendency and the friction factor of each mud sample.
- Calculating the theoretical release force for each stuck pipe incident.

6.1. Drilling Fluid Sample Formulations

Though it was impossible to create samples that are identical to the field muds, five primary mud properties were identified, which play a crucial role in differential sticking. These are:

- drilling fluid density (MW),
- plastic viscosity (PV),
- yield point (YP),
- gel strengths (GS) (both 10 sec and 10 min),
- fluid loss (FL).

Therefore the intention was to mix mud samples and set the above mentioned parameters so that the properties of the laboratory samples would be the same as those recorded in the daily reports. For this purpose a variable RPM mud blender made by Chandler Engineering was used. Anyone who has ever dealt with drilling fluids knows the difficulty of treating and maintaining the properties needed to deliver the required functions. Almost all the variables affect each other, for instance one cannot change the density or fluid loss without altering viscosity. Therefore trade-offs were required, which resulted in lab samples that are slightly different than the mud used in the field. Table 2 describes the field mud properties against the lab sample parameters. The θ600 and θ300 values were computed using equations 5.4 and 5.5.

Mud properties	Mud #1		Mud #2		Mud #3		Mud #4	
	Field	Lab	Field	Lab	Field	Lab	Field	Lab
MW [kg/l]	1.63	1.63	1.12	1.12	1.39	1.39	1.15	1.15
PV [cP]	48	43	18	21	25	29	24	30
YP [lb/100 ft^2]	22	23	16	8	14	9	30	15
GS 10 s/10 min [lb/100 ft^2]	7/23	4/23	5/5	2/6	3/5	3/7	7/8	3/9
FL [ml/30 min]	4.1	6	5.0	7	3.6	6	4.7	6
θ600 [Fann]	70	66	34	29	39	38	54	45
θ300 [Fann]	118	109	52	50	64	67	78	75

Table 2: Field and lab mud properties

The main challenges – when setting the mud parameters – were the following. Increasing the θ600 and θ300 values independently lead to a very limited success. Though adding polymers (CMC) to increase viscosity slightly increased the gap between θ600 and θ300, only minor alterations could be accomplished by doing so. The other concern was the fluid loss control. It is thought that the absence of micro-sized drilled solid particles caused the something higher fluid loss values of lab muds compared to the field muds. Adding more fluid loss additive had no effect on filtration after reaching the 6 ml/30 min line. An attempt was made to enhance fluid loss control by adding graphite powder to the lab samples, but no improvements were recorded at all. As some authors suggest, graphite may be sufficient only in conjunction with nano-sized synthetic polymers and sized calcium carbonate. *(Al-Haj et al. 2016)* Finally, in case of Mud #2, #3 and #4, 10 sec and 10 min gel strengths had almost the same values. This could not be achieved in the lab using the available additives, but despite this fact, the aim was to set the gel strengths of the lab samples with maximum accuracy according to the daily reports.

Additive	Function
Barite	Weighting agent
Bentonite	Rheology and fluid loss control
Carboxymethyl-cellulose (CMC)	Rheology and fluid loss control
PolyPac UL	Fluid loss control
Lampac Lovis	Fluid loss control
Polydrill	Fluid loss control

Table 3: Additives and their functions used for creating the lab samples

Though all the examined mud properties could be modified in the lab, the number of available products was limited; therefore only clay drilling fluids were mixed. The examined wells were drilled by applying WBFs, so the base fluid was tapwater for all samples. To simplify the task, pH adjustments were neglected. Table 3 shows the additives used for blending the drilling fluid samples and their functions.

PolyPac UL (by M-I SWACO), Lampac Lovis (by Lamberti) and Polydrill (by BASF) are products which consist of water soluble polyanionic-cellulose polymers. As opposed to CMC, they produce minimum viscosity increase while improving filter cake quality and reduce fluid loss. These additives showed quite similar results in filtration control, yet Lampac Lovis was found to deliver the best quality cake with minimum thickness. Cake thickness varied between $^{1}/_{32}$ and $^{2}/_{32}$ in (0.8 and 1.6 mm).

Creating the proper laboratory mud samples took a significant amount of time; the final formulations are described in Table 4. As previously mentioned, treating the mud samples with Lampac Lovis lead to the best results concerning fluid loss control, so finally this product alone was used as a polyanioic-cellulose additive. The overall quantity of the additives was set so that a sufficient volume of drilling fluid would be available for testing.

Additives	Mud #1	Mud #2	Mud #3	Mud #4
Tapwater [ml]	330	400	330	400
Barite [g]	350	65	190	20
Bentonite [g]	15	20	15	75
Lampac Lovis [g]	1.5	2	1.7	3
CMC [g]	0.2	-	-	-

Table 4: Laboratory mud sample formulations

6.2. Determining the Friction Factor

The measurements for this section were carried out with a Fann Differential Sticking Tester. The tests were run in order to define the friction factor for each mud sample. Therefore data were provided for the calculation process when theoretical pullout force values were computed for each stuck pipe event. The short description of this instrument can be found in Chapter 5.3.4, the exact testing process is described below:

- Blending the lab drilling fluid samples in accordance with the previously specified mud formulations.
- Assembling the DST, then filling the cell with the sample fluid.

- Closing the cell and adjusting the pressure regulator to the pre-determined value. This value represents the differential pressure in the borehole.
- Allowing the drilling fluid to filter for 10 min, then recording the volume of filtrate.
- Pressing the torque plate down against the filter cake, then allowing the plate to stick for 10 min.
- Placing the torque wrench on the top of the plate stem and measuring the required release torque in every 30 s.
- Repeating torque measurement six times or until the upper limit of the measuring range has been reached (300 lb*in).
- Calculating the average release torque.

The following consideration had to be made regarding the applied differential pressure. As only drilling daily reports were available for each well, the formation pressures in the boreholes were unknown. An effort was made to estimate the formation pressure by examining the total gas, background gas, connection gas and trip gas values, as well as the change in drilling fluid density, but due to the numerous unknown variables, this attempt has been rejected. Therefore – as the DST Instruction Manual suggests – a differential pressure of 480 psi was applied. *(Fann 2010)*

The tests were run with two different cell assemblies, first with the locking mesh disc, then without it. The locking mesh disc (Figure 16) is an optional part of the instrument. In such events when the filter cake tends to adhere more to the torque plate than to the filter paper, this steel micro-corrugation disk should be applied to prevent this happening. Though the lab samples created for this thesis were quite „sticky", the mud cakes were not thick enough to hold the torque plate when using the mesh disc; therefore valid release torque values were obtained in absence of the disc (Table 5).

Time [s]	**$Torque_{Mud\ \#1}$ [lb*in]**	**$Torque_{Mud\ \#2}$ [lb*in]**	**$Torque_{Mud\ \#3}$ [lb*in]**	**$Torque_{Mud\ \#4}$ [lb*in]**
30	200	150	175	175
60	250	170	200	190
90	275	200	220	210
120	300	220	250	220
160	-	230	270	230
180	-	245	300	240
Average	**256**	**202**	**235**	**211**

Table 5: Release torque values as obtained from the measurements with DST

As the DST Instruction Manual says, the friction factor can be calculated using the average torque reading, applying the following equation. *(Fann 2010)*

$$f = \frac{Torque_{avg}}{1000 \cdot R^3} \tag{6.1}$$

Where:

f: friction factor between mud cake and steel [-]

$Torque_{avg}$: average torque reading as determined previously [lb*in]

R: radius of the torque plate [in]

The torque plate used for the tests had a diameter of 2 in. Applying equation 6.1, the results are described in Table 6.

	Mud #1	Mud #2	Mud #3	Mud #4
Friction factor [-]	**0.256**	**0.202**	**0.235**	**0.211**

Table 6: Calculated friction factors of the laboratory mud samples

The friction factor of a proper drilling fluid varies from 0.15 to 0.50; therefore the calculated values are in accordance with field experience. *(Schlumberger 1999)* Comparing the drilling fluid parameters in Table 2 to the calculated friction factors, a straightforward correlation between density/solid content and friction factor can be recognized (Figure 17).

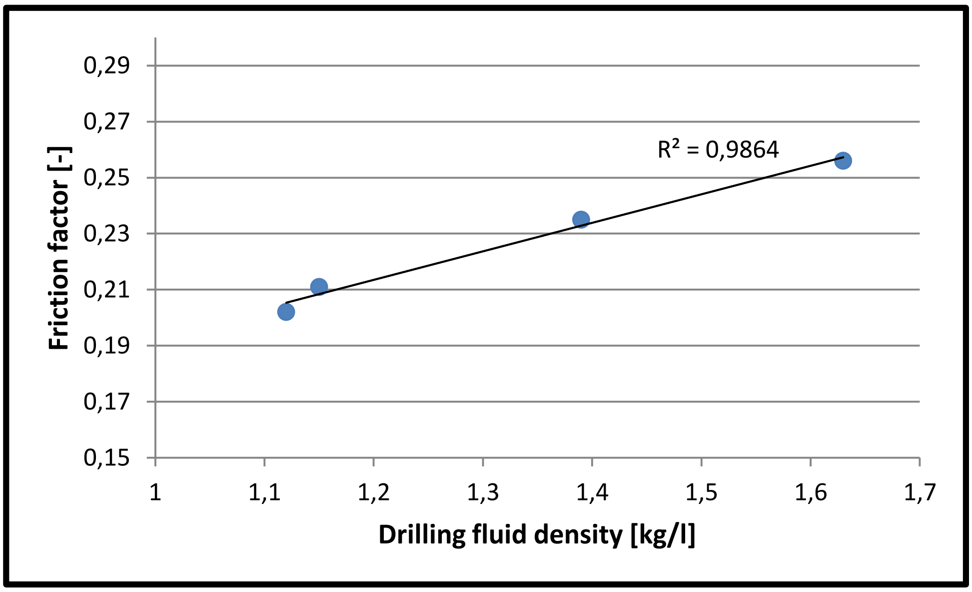


Figure 17: Correlation between drilling fluid density and calculated friction factor

6.3. Calculating the Theoretical Pullout Force

In order to calculate the theoretical pullout or friction force (F); differential pressure (p_d), total contact area (A_c) and friction factor between the mud cake and the pipe (f) have to be determined. A more accurate result would be available by using equation 2.6, but measuring the solid and hydraulic stresses acting in the cake are beyond the limits of this thesis. Therefore results are obtained by applying equation 2.3 and calculating the friction force for each stuck pipe case.

To simplify the task, the assumption was made that the drill collars were stuck differentially in all cases. Table 7 summarizes the wellbore geometry for each stuck pipe incident.

Stuck pipe incident	Hole size [in]	Drill Collar outer diameter [in]	Pipe-to-hole ratio [-]
Stuck Pipe #1	8 $^{1}/_{2}$	6 $^{1}/_{2}$	0.765
Stuck Pipe #2	12 $^{1}/_{4}$	8	0.653
Stuck Pipe #3	8 $^{1}/_{2}$	6 $^{1}/_{2}$	0.765
Stuck Pipe #4	6	4 $^{3}/_{4}$	0.792

Table 7: Well geometry for each stuck pipe incident

Another problem arises when computing the total contact area. Though some authors *(Rabia 2001)* suggests, that for practical purposes the contact area should be determined by assuming that 20% of the perimeter of the stuck pipe became embedded in the filter cake, more precise calculations should be applied. For this thesis an analytical method was used, the input data were the following: hole size, outer diameter of the drill collars and embedded depth. The angle of contact could be determined by calculating the intercept points of two eccentric circles, one of which represents the pipe and the other stands for the mud cake on the borehole wall, assuming that the stuck pipe is embedded totally in the cake (Figure 18). The calculations were performed by using an engineering mathematical software, Mathcad by PTC. The contact circumference between the mud cake and the pipe could be determined as well, using the equation below.

$$C_c = \pi \cdot OD_{DC} \cdot \frac{\alpha_c}{360^\circ} \tag{6.2}$$

Where:

C_c: contact circumference between filter cake and drill collar [m]

OD_{DC}: outer diameter of drill collars [m]

α_c: angle of contact [°]

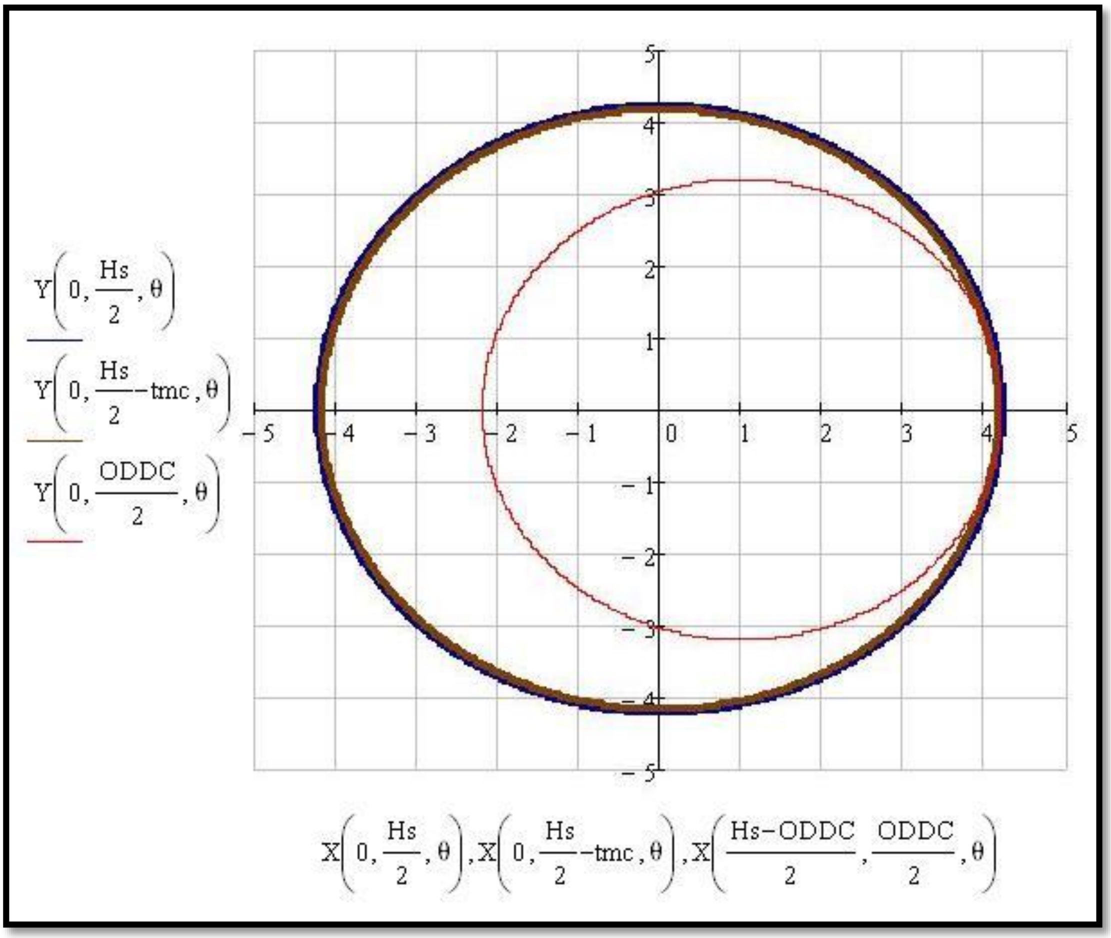


Figure 18: Determining the angle of contact. Blue, brown and red circles represent the borehole, mud cake and DC respectively.

As mud cake thickness recorded by standard filtration tests are not equivalent to the actual thickness in borehole conditions, the calculations were carried out with different hypothetical embedded depths (1, 2, 4, and 6 mm). The final parameter required to determine the contact area is the length of the stuck drill collars. Again, the lack of exact information about the thickness of the permeable formations where the DCs became stuck meant that only estimations could be given. Calculations were carried out applying different lengths of stuck DCs (6, 12, 18 and 24 m). The reduction in contact area due to the spiral DCs was neglected. Finally, contact area is as follows.

$$A_c = C_c \cdot l_{DC} \quad (6.3)$$

Where:

A_c: total contact area between filter cake and drill collar [m^2]

C_c: contact circumference between filter cake and drill collars [m]

l_{DC}: length of stuck drill collar [m]

Mud cake thickness [mm]	Stuck Pipe #1	Stuck Pipe #2	Stuck Pipe #3	Stuck Pipe #4
1	28.2°	17.9°	28.2°	36.4°
2	40.1°	25.3°	40.1°	51.9°
4	57.2°	35.9°	57.2°	74.4°
6	70.7°	44.1°	70.7°	92.5°

Table 8: The angle of contact against the mud cake thickness

Table 8 describes the angle of contact for each stuck pipe event, assuming the aforementioned hypothetical embedded depths. Examining the results, they show that the angle of contact rises as the pipe-to-hole ratio (Table 7) increases.

The total contact area was calculated for each stuck pipe incident assuming four different mud cake thicknesses (t_{mc}) and four different lengths of stuck drill collars (l_{DC}), moreover the theoretical pullout force for each stuck pipe incident was determined. Tables 9, 10, 11 and 12 show these results. The pullout force values were converted to tonne units for practical purposes.

l_{DC} \ t_{mc}	1 mm	2 mm	4 mm	6 mm
6 m	21.1 t	29.9 t	42.7 t	52.8
12 m	42.4 t	59.8 t	85.4 t	105.6 t
18 m	63.3 t	89.7 t	128.1 t	158.4 t
24 m	84.4 t	119.6 t	170.8 t	211.2 t

Table 9: Required theoretical overpull to initiate release in case of Stuck Pipe #1

In case of Stuck Pipe #1 the hole size was $8^1/_2$ in, while the outer diameter of the drill collars were $6^1/_2$ in. Mud sample #1 had the highest friction factor of 0.256.

l_{DC} \ t_{mc}	1 mm	2 mm	4 mm	6 mm
6 m	13.0 t	18.3 t	26.0 t	32.0 t
12 m	26.0 t	36.6 t	52.0 t	64.0 t
18 m	39.0 t	54.9 t	78.0 t	96.0 t
24 m	52.0 t	73.2 t	104.0 t	128.0 t

Table 10: Required theoretical overpull to initiate release in case of Stuck Pipe #2

The wellbore geometry for Stuck Pipe #2 was as follows: hole size $12^1/_4$ in, drill collar outer diameter 8 in, while the friction factor of mud sample #2 was 0.202 which is the lowest among the lab samples.

t_{mc} / l_{DC}	1 mm	2 mm	4 mm	6 mm
6 m	**19.4 t**	**27.5 t**	**39.2 t**	**48.5 t**
12 m	**38.8 t**	**55.0 t**	**78.4 t**	**97.0 t**
18 m	**58.2 t**	**82.5 t**	**117.6 t**	**145.5 t**
24 m	**77.6 t**	**110.0 t**	**156.8 t**	**194.0 t**

Table 11: Required theoretical overpull to initiate release in case of Stuck Pipe #3

As for Stuck Pipe #3, a wellbore with a diameter of $8^1/_2$ in was drilled, the BHA included drill collars with outer diameter of $6^1/_2$ in. Mud sample #3 had a moderate friction factor of 0.235.

t_{mc} / l_{DC}	1 mm	2 mm	4 mm	6 mm
6 m	**16.4 t**	**23.3 t**	**33.5 t**	**41.6 t**
12 m	**32.8 t**	**46.6 t**	**67.0 t**	**83.2 t**
18 m	**49.2 t**	**69.9 t**	**100.5 t**	**124.8 t**
24 m	**65.6 t**	**93.2 t**	**134.0 t**	**166.4 t**

Table 12: Required theoretical overpull to initiate release in case of Stuck Pipe #4

In case of Stuck Pipe #4, the hole size was 6 in with $4^3/_4$ in drill collars. The pipe-to-hole ratio was the highest of the examined four boreholes. Mud sample #4 had the second lowest friction factor with a value of 0.211.

Stuck Pipe #1	Stuck Pipe #2	Stuck Pipe #3	Stuck Pipe #4
60 t overpull	100 t overpull	75 t overpull	65 t slack-off
Release failed	**Release failed**	**Released**	**Release failed**

Table 13: Release attempts immediately after sticking occurred, as obtained from field data

Table 13 shows the first attempts in order to free the pipe immediately after sticking occurred. As for cases #1, #2, and #4, the first jarring attempt was insufficient. Therefore the drilling fluid was displaced at the stuck point by spotting fluid (Pipe-Lax), and jarring was continued until the pipe was pulled free. Additional torque was used for maximum efficiency as well. In the first case (Stuck Pipe #1), jarring was continued with hook load values between 30 and 175 t; release could be initiated after 40 hours with an overpull of 80 t. In the event of Stuck Pipe #2, even pumping spotting fluid in the annulus while jarring and applying hook load between 15 and 175 t were insufficient for two days. Finally the pipe was freed after 53 hours with a slack-off of 25 t. As for the last event (Stuck Pipe #4), freeing procedure took 38 hours applying slack-off between 30 and 65 t, at last the pipe was released with an overpull of 45 t. In case of Stuck Pipe #3, spotting was not required, as the pipe could be pulled free instantly with an extra hook load of 75 t.

When comparing the required theoretical overpull values (Tables 9, 10, 11, 12) to the actual field records (Table 13), important notes about the assumed mud cake thicknesses and stuck lengths can be made. The calculated overpulls, which are below the actual overpull/slack-off applied during the first freeing attempt, are indicated with green. In these cases the stuck pipe would be freed theoretically. When the required overpull exceeds the actual value, the numbers are recorded in red, which means that the hypothetical release failed. As the outcomes of the first attempts are known, the possible values of mud cake thickness and stuck pipe length are easily recognized for each incident.

Stuck Pipe #1 remained stuck at first, so the values in red are valid for this case, which means relatively long stuck pipe intervals. Release was failed for Stuck Pipe #2 too; hence the most likely values are long intervals of stuck pipe and a thick filter cake. As Stuck Pipe #3 was freed, the green records should be examined. Potential parameters are thin mud cakes and/or short stuck pipe intervals. As for Stuck Pipe #4, the red numbers are valid again, namely long stuck pipe intervals and/or thick filter cakes.

7. CONCLUSIONS

Several difficulties arose while simulating stuck pipe incidents. The most significant obstacles were as follows:

- As drilling daily reports were the only source of information, the lack of important data regarding geology, mud logs and drilling fluid formulation meant that only estimations could be given in some cases. Therefore important input parameters, such as differential pressure, mud cake thickness and stuck pipe interval had to be set without knowing the actual wellbore conditions.
- Due to the limited range of available drilling fluid additives, the tests were run with clay water based drilling fluids, while the operator applied polymer drilling mud. Though the mud parameters were set as precisely as possible, this difference in generic mud type could lead to significant alterations when determining the friction factor.
- All of the examined stuck pipe events happened several years ago, therefore the possibility to specify certain unclear details was impracticable.

Despite the above mentioned difficulties, the calculated theoretical overpull values could be compared to the actual overpulls applied immediately after sticking occurred. Therefore assumptions could be made concerning the most likely mud cake thicknesses and stuck drill collar lengths. This may proved the efficiency of the applied calculation method.

As for the future plans, two possible application methods have to be mentioned:

- The effectiveness of the Pipe-Lax spotting fluid could be investigated in laboratory conditions, by simulating the spotting procedure with the Differential Sticking Tester. The decrease in the required release torque should be examined with respect to time.
- The friction factor values obtained from the measurements with the Differential Sticking Tester were in accordance with the differences between the various mud sample formulations. It means that trends in the sticking potential of drilling fluids can be recognized; and the DST could be used at drillsite to identify effective mud treatments which reduce the risk of differential sticking.

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ÖSSZEFOGLALÁS

A szerszámmegszorulások az egyik legkomolyabb problémának számítanak a mélyfúrásban, a fúrási problémák megközelítőleg harmada erre vezethető vissza. Egyes becslések szerint ezek az esetek évente több százmillió dolláros többletköltséggel járnak. Az esetek súlyossága nagy szórást mutathat, végső esetben az adott lyukszakasz felhagyása és kiferdítése is szükségessé válhat A megelőzéshez fontos ismerni a különböző típusú megszorulások okait és jeleit, mivel a nem megfelelő beavatkozás könnyen ronthat a helyzeten.

A differenciális megszorulás leírása C. S Penfield nevéhez fűződik, aki a Shell kútmunkálati felügyelőjeként dolgozott. Komoly kihívást jelentett differenciális megszorulás szempontjából a fúrási munkálatok elterjedése a Mexikói-öbölben, ahol a túlnyomásos formációk harántolása rutinszerű volt, ezáltal a túlegyensúlyozás értékét magasan kellett tartani. Ezzel egyidejűleg az irányított szakaszok fúrása is egyre gyakoribbá vált, ami egyúttal a permeábilis rétegek fúrásánál egyre hosszabb kitett szakaszokat jelentett. A differenciális megszoruláshoz köthető lyukproblémák számának újabb növekedése az 1990-es évek végén következett be, ahogy a horizontális lyukszakaszok fúrása elterjedt. Ezzel együtt a mentési költségek is növekedtek az egyre magasabb berendezés napidíjak és egyre kifinomultabb lyuktalpi eszközök miatt. Ahogy a kimerült szénhidrogén-tárolók száma nő, több és több kútnál lesz szükséges nagy túlegyensúlyozást tartani, ami együtt jár majd a differenciális megszorulás veszélyével. Ezért is fontos pontosan megérteni a differenciális megszorulás pontos mechanizmusát és a lehetséges megelőzési lehetőségeket.

Szakdolgozatomban sorra vettem a differenciális megszorulásra hatással levő fúrási paramétereket, majd részletesen kitértem a fúróiszap-tulajdonságok hatására is a szakirodalom lehető legteljesebb tanulmányozásával. A megelőzés és a szabadítás lehetséges módozatait is áttekintettem. Ezután egy operátortól kapott adatok alapján – amely cég tevékenysége során számos differenciális megszorulás előfordult az utóbbi években – laboratóriumi körülmények között próbáltam a lehető legpontosabban szimulálni az egyes fúrás közbeni szerszámmegszorulásokat. A kutatás kezdetén az adott fúrásoknál alkalmazott iszapokat rekonstruáltam a legfontosabb iszapparaméterek alapján, majd ezen iszapok súrlódási együtthatójának számítását végeztem el egy erre a célra tervezett speciális eszközzel (Fann Differential Sticking Tester). Végül a megszorult szerszám megszabadításához szükséges szabadító erő nagyságát határoztam meg különböző feltételezett iszaplepény-vastagságokat és megszorult szerszámszakasz-hosszokat alapul véve. Az így kapott eredményeket összehasonlítottam a fúrás közben rögzített adatokkal, végül a módszer esetleges terepi és laboratóriumi alkalmazásával kapcsolatban vontam le következtetéseket.

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