TORQUE AND DRAG APPLICATIONS FOR DEVIATED AND HORIZONTAL WELLS: A CASE STUDY

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
PETROLEUM AND NATURAL GAS ENGINEERING

DECEMBER 2014

Approval of the thesis:

TORQUE AND DRAG APPLICATIONS FOR DEVIATED AND HORIZONTAL WELLS: A CASE STUDY

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ABSTRACT

TORQUE AND DRAG APPLICATIONS FOR DEVIATED AND HORIZONTAL WELLS: A CASE STUDY

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December 2014, 115 pages

One of the most critical limitations during hydrocarbon exploration, especially during directional drilling, is torque and drag generated by the contacts between the drill string and the borehole or casing. Therefore, torque and drag analysis and calculations are very important for well design to prevent equipment and economical losses. Proper modeling is highly important to predict and prevent downhole problems related to drill string and borehole, beforehand commencing to the activities if not during the course of the drilling campaign.

In order to emphasize the importance of torque and drag in drilling activities, many studies were conducted and different models are already developed in literature. In this study, a synopsis of the important literature on torque and drag studies is demonstrated. An easy to use torque and drag calculation model based on Soft String Theory is constructed to be used in field drilling case applications for deviated and horizontal wells.

The torque magnitude on the torque sensor while drilling is the cumulative torque measured which is the result of frictional and rotational torque values. Only the magnitude of frictional torque can be calculated by Soft String Theory. In order to construct a torque and drag model based on this theory, several parameters such as drill string components and drill string weight, casing depths, friction factors, drilling fluid density, well inclination and azimuth are considered and employed in the model. Histograms are generated for error comparison with the actual well data and an overall of 85% of data are observed to be calculated with less than 20% of error margin. For model validation purposes, the actual rotational torque values while drilling are back calculated; together with the pick-up (up move) drag in the scope of this study. It is expected that the oilfield personnel are going to be using the proposed methodology of torque and drag calculations while drilling deviated wells.

Keywords: Torque and drag, wellbore friction, drill string failure, directional drilling, horizontal well

ÖZ

YÖNLÜ VE YATAY KUYULAR İÇİN TORK VE SÜRTÜNME UYGULAMALARI ÜZERİNE BİR SAHA ÇALIŞMASI

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Aralık 2014, 115 sayfa

Hidrokarbon aramaları sırasında özellikle yönlü sondaj kuyularında sondaj dizisi, açık kuyu ve muhafaza boruları arasında ortaya çıkan en önemli kısıtlayıcı etkiler tork ve sürtünmedir. Bu yüzden, sondaj kuyusu dizaynında tork ve sürtünme analizi ve hesaplamaları ekipman ve ekonomik zararları önlemek adına çok önemlidir. Sondaj dizisi ve kuyu içi problemlerinin aktivitelere başlamadan veya sondaj çalışmaları sırasında öngörülebilmesi ve önlenebilmesi için uygun bir modelleme kullanılması da oldukça önemlidir.

Sondaj aktiviteleri kapsamında tork ve sürtünmenin öneminini vurgulamak amacıyla birçok çalışma yapılmış ve literatürde farklı modellemeler geliştirilmiştir. Bu çalışmada, literatürde şimdiye kadar yapılmış önemli tork ve sürtünme çalışmalarının özetleri verilmiştir. Yönlü ve yatay kuyu sondaj saha uygulamalarında kullanılmak üzere kolayca kullanılabilecek, Yumuşak Dizi Teorisi'ne dayanan bir tork ve sürtünme hesaplama modeli oluşturulmuştur.

Sondaj sırasında tork sensöründe gözlenen değer sürtünme ve sondaj dizisinin dönmesiyle meydana gelen toplam tork değeridir. Bu teori ile yalnızca sürtünme nedeniyle oluşan tork değerleri hesaplanabilir. Bu teoriye dayanan bir tork ve sürtünme modeli oluşturabilmek için sondaj dizisi aksamları ve ağırlıkları, muhafaza borularının derinlikleri, sürtünme katsayısı, sondaj sıvısının yoğunluğu, kuyunun eğimi ve yönü gibi birçok değer dikkate alınmış ve modelde kullanılmıştır. Gerçek kuyu verileriyle hata karşılaştırması için histogramlar oluşturulmuş ve verilerin %85'lik kısmının %20 altında hata payı ile hesaplandığı gözlenmiştir. Çalışmanın kapsamında, modelin geçerliliğini denetlemek amacıyla sondaj esnasında dizi dönüşünden kaynaklanan asıl tork değerleri geri hesaplamayla bulunmuş, dizinin çekilmesi (yukarı hareketi) esnasındaki sürtünme değerleriyle beraber hesaplanmıştır. Petrol sahalarında çalışan personelin önerilmekte olan tork ve sürtünme hesaplamaları metodunu yönlü kuyu sondajlarında kullanmaları beklenmektedir.

Anahtar kelimeler: tork, kuyu içi sürtünme, sondaj dizisi arızası, yönlü sondaj, yatay kuyu

ACKNOWLEDGMENTS

I would like to express my appreciation and respect to my supervisor Prof. Dr. Mustafa Verşan Kök for his valuable experience and contributions on this study.

I would also like to thank my co-supervisor Assist. Prof. Dr. Tuna Eren for being the driving force in this study, his constant support, guidance and encouragement. His contributions on the torque and drag model construction are invaluable.

I would like to thank Prof. Dr. Mahmut Parlaktuna, Assist. Prof. Dr. Çağlar Sınayuç and Dr. Reha Özel for their valuable comments and feedback.

I am grateful to my previous employer Baker Hughes in which I gained considerable technical experience in drilling, directional drilling and measurement while drilling technologies while working at rig site. I also appreciate my current employer Perenco in which I can still enhance my knowledge in the drilling industry.

I am proud of my parents who had grown two children with many sacrifices. They have been the main force and guide during my education and transfused many principles into me such as honesty, determination and passion for success.

Special thanks to my wife who has always been beside me with her continuous love and support.

Finally, I appreciate all oilfield workers who work in harsh conditions to feed their families.

To My Parents,

Brother,

and

Wife

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NOMENCLATURE

Roman

F	Force Vector, lbf
F_n	Normal force, lbf
F_t	Tension Force, lbf
W	Weight, lbf
M	Torsion at the lower end of element, ft-lbf
R	Radius, ft
r	Vector of Displacement, ft

Greek

τ	Torque, ft-lbf
Δ	Delta
ϕ	Azimuth, degree
θ	Angle (Inclination), degree
ρ	Mud Weight, ppg
μ	Coefficient of Friction

Abbreviations

MLU	Mud Logging Unit
AKO	Angle of Kick-Off, degree
Az	Azimuth, degree
BF	Buoyancy Factor
BHA	Bottom Hole Assembly

DC	Drill Collar
DLS	Dogleg Severity
DST	Drill Stem Test
ECD	Equivalent Circulating Density, ppg
ERD	Enhanced-Reach Drilling
HWDP	Heavy Weight Drill Pipe
ID	Inner Diameter, ft
Inc	Inclination, degree
MD	Measured Depth, ft
MWD	Measurement While Drilling
NRDPP	Non-Rotating Drill Pipe Protector
OD	Outer Diameter, ft
PDC	Polycrystalline Diamond
ROP	Rate of Penetration, rop
RPM	Revolutions per Minute, rpm
RSS	Rotary Steerable System
SG	Specific Gravity
TDS	Top Drive System
TVD	True Vertical Depth, ft
WOB	Weight on Bit, lbf
NPT	Non-productive Time
OH	Open-hole
HPHT	High Pressure, High Temperature

CHAPTER 1

INTRODUCTION

With the increasing demand in the oil industry, directional drilling has become important and widespread to minimize overall development production costs of an oilfield, especially for the following considerations:

- Improve hydrocarbon production by drilling horizontal wells; hence, developing thin reservoirs [1].

- Rig cost might be reduced by drilling multiple wells from same rig site or platform (Figure I).

- There is a global need to drill development wells directionally in fields over which due the surface obstructions there is no other option.

Figure I - Drilling Multilateral Wells Over Same Location [2].

Directional drilling is the science of deflecting a wellbore in a particular direction of a pre-determined target below the surface [3]. Ability to rotate and reciprocate the drill string in highly deviated and large displacement wellbores is one of the major concerns in directional drilling [4].

Today, with the improvement of the technology, there developed two commercial methods to achieve a deviated or horizontal well namely, rotary steering systems (RSS) and MWD/motor systems. Rotary steering systems are designed in a way that the entire drill string rotates with steering capacities. This system provides a continuous rotation while drilling in any sections of the deviated well. On the other hand, MWD/motor systems are configured with an MWD – measurement while drilling – surveying tool for data transmission, a steerable downhole mud motor with a bent housing (Figure II). This system is used for drilling a tangent section with continuous rotation and/or a curve with rotating the bit only (sliding).

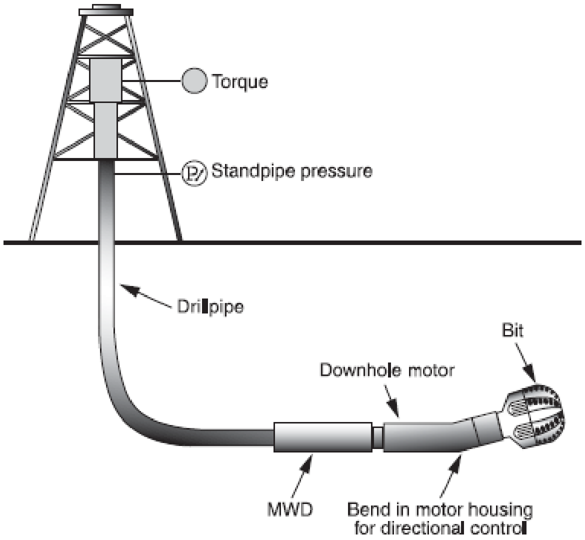


Figure II - MWD/Motor System [5].

The rotary steerable systems provide accurate directional control of the borehole via closed-loop steering system (Figure III). The rotary steerable systems are higher cost equipment but using these kinds of systems would increase penetration rates during the directional drilling of a well because there are no stationary components to create friction (no stick-slip phenomena). RSS technologies are believed to account for about $3.5 billion of the estimated $15 billion directional drilling market [6]. In order to determine which system to select for the drilling operation drilling costs, availability of the technology and logistics of the particular rig site should be considered [7].

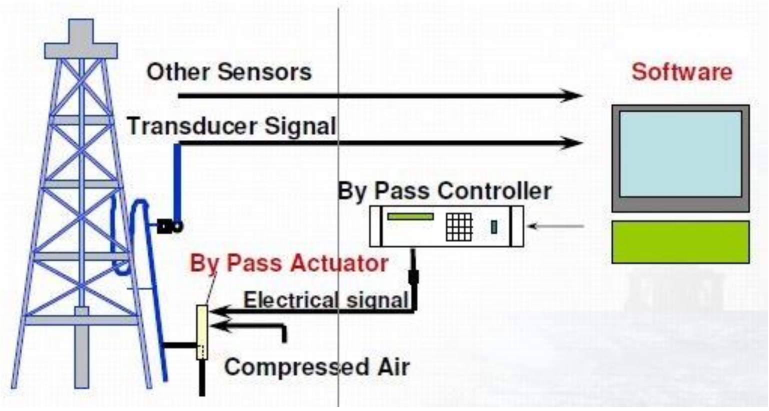


Figure III - RSS Closed-Loop System.

Despite many benefits, directional drilling brings a lot of limitations during the operations and needs a lot of engineering work because optimizing the drilling parameters becomes more sophisticated as the well gets deeper with the well trajectory changes. Two of the most important limitations are torque and drag which are generated by the friction between the borehole and drill string. Therefore, optimizing drilling parameters to reduce or prevent torque and drag is critical in order to maintain the well condition, prevent drill string failures and reduce drilling costs [1].

The loss of power due to the friction on the drill string that occurs because of the difference between the power available at the bit and the power applied at the rotary table is regarded as torque. Torque is being observed when the drill string is under revolution. Drag is the load difference between the static weight of the drill string and the tripping weight of the drill string observed. Excessive torque and drag are found to be occurring together [8]. Torque and drag problems are associated with each other and may be profound in extended-reach and horizontal wells.

There are some sources which would result in torque and drag such as high friction between drill string and borehole, wellbore tortuosity and hole cleaning problems. Excess torque and drag mainly occur from the friction between wellbore and drill string. Hole profiles and tortuosity determine the severity of friction. Wellbore tortuosity is defined as the deviation of the wellbore compared to the planned trajectory and it affects over the surface torque for effective drilling. High tortuosity affects hole cleaning negatively such that an additional time for circulation of drilling fluid, back-reaming and short trips will be required to transfer trapped cuttings from the wellbore to the surface. Trapped cuttings result in resistance that prevents drill string rotation and penetration; hence, increase surface torque [9]. Therefore, precautions must be taken to keep the torque and drag within the allowable limits. Lower torque and drag might have significant improvements on drilling operations like higher ROP and increase in drilling interval [10].

Torque and drag modeling is one of the essential parts of designing a well. Parameters such as drill string components, their weights, casing depths, formation types and frictional forces, drilling fluid density, well profile (inclination and azimuth) should be considered in every torque and drag model. Torque and drag modeling is not only considered a priceless step to assist in well planning but also regarded as a helpful process to predict and prevent drilling problems [11].

It is observed that the field personnel are lacking details of torque and drag theory and a modeling tool to make quick calculations regarding whether the ongoing drilling process is within the torque and drag limitations of the drill string. This study is dedicated to provide an in depth knowledge to field personnel on torque and drag theory and a calculation tool to make quick computations and take immediate decisions during drilling operations.

In order to solidify the study, data for five (5) wells are used to test the introduced methodology. The data of the wells are acquired by means of the Mud Logging Units (MLU). The actual data is captured for each 0.5 m interval. The wells are planned to be drilled through a single azimuth to ensure a smooth wellbore is drilled. The rotational torque while drilling at the bit in the calculations for each and every analysis is estimated between 2000 - 4000 lbf.ft respectively based on actual hole conditions. Eventually, torque and drag trends are generated by the model proposed in this study, the model and the calculated torque and drag data are compared and actual rotational torque values are back calculated.

CHAPTER 2

LITERATURE OVERVIEW

Torque and drag are the two factors that are generally observed in extended-reach and horizontal drilling as weight applied on the bit increases with increasing depth along the same formations; and ability to drill efficiently decreases with higher inclinations. In addition, it is also possible to encounter torque and drag during vertical or directional drilling applications, especially if a proper monitoring is not performed and miscalculated drilling parameters are used. Therefore, torque and drag predictions in pre-planning phase of a well may be in nonconformity with drilling plans [12].

Aarestad, 1994 [13] in his study declared that, excessive torque and drag are associated with each other and expected to be found together in extended-reach and horizontal drilling cases. In any case, a close monitoring and appliance of correct calculations are necessary to keep torque and drag within permissible limits that would maintain the drill string without a failure. Beyond all, a modeling must be performed and precautions must be taken before the drilling commences.

2.1 Understanding Torque and Drag

For a better understanding of torque and drag; their definitions, sources, types, and challenges they bring about and reduction techniques must be carefully examined and previous investigators' works should be studied. The better they are understood, the easier will be to interpret the ongoing drilling activities from torque and drag view.

2.1.1 Definitions

Aarestad, 1994 [13] defined torque in his study as the power lost due to friction while transferring surface torque to bit. He similarly defined drag as the difference of static and tripping weight of the drill string. As Mitchell [14] designated in his book, torque and drag refers to the effects of turning and pulling the drill string on wellbore geometry during sliding and rotary drilling. Drill string is not rotated in sliding mode; hence, torque is expected to be low. On the contrary, axial drag is expected to be high and lock-up is possible which means a partial buckling of the drill string, leading to the problems related to the weight transfer to the drilling bit. On the other hand, in the rotary drilling mode, torque is expected to be high with the rotation of the drill string and drag is expected to be insignificant, so is the lock-up.

2.1.2 Sources

Johancsik et al., 1984 [15], specified the causes for excessive torque and drag as hole instabilities, key seating, differential sticking, poor hole cleaning and wellbore friction.

- **Hole Instability:** Hole instability is a displeasing case that occurs when the original hole size, shape and structural conditions of a borehole are not well maintained. It appears with the failure of balance between the rock strength and in-situ rock stress at some depth during drilling. It may also arise with the effects of drilling fluid such as erosion in the borehole and chemical interactions of drilling fluid with drilled formation. Hole closure, which is the narrowing process of borehole, results in an increase of torque and drag [16].

- **Key Seating:** Key seating is the condition when a tubular of a small diameter is worn into the side of a larger diameter borehole (Figure IV). It is generally a result of severe hole direction changes such as a high dogleg or a hard formation ledge left in soft formations which erodes and enlarges in time. In both cases, the diameter of the drilled hole is expected to be close to the diameter of the drill pipe. The larger diameter tools such as stabilizers, drill collars and tool joints are not able to pass through the key seat and become stuck which will result in problems associated with high torque and drag. The preventive method is to enlarge the point of key seat so that the tools with larger diameters can pass through it [17], [18].

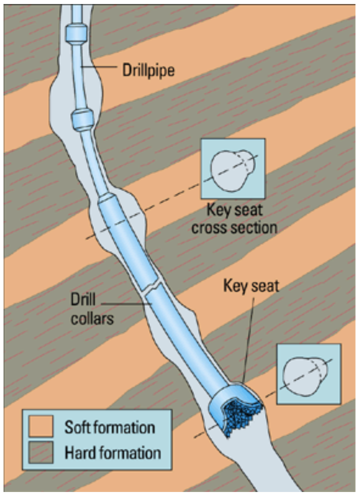


Figure IV - Key Seating [17].

- **Differential Sticking:** For most of the drilling organizations, differential sticking is the biggest problem regarding time and financial cost. Differential sticking is the condition of being unable to rotate or move the drill string along the axis of wellbore due to embedding of a part drill string in the mud cake that is formed on the wall of a permeable formation. It typically occurs when low reservoir pressures and/or high wellbore pressures cause high contact forces over a large portion of a drill string (Figure V). Differential pressure appears when the hydrostatic pressure of a drilling fluid acting on the outside wall of the drill pipe is greater than the formation fluid pressure and results in a sticking force. An indication of differential sticking is an increase in torque and drag relative to the actual drilling values [8].

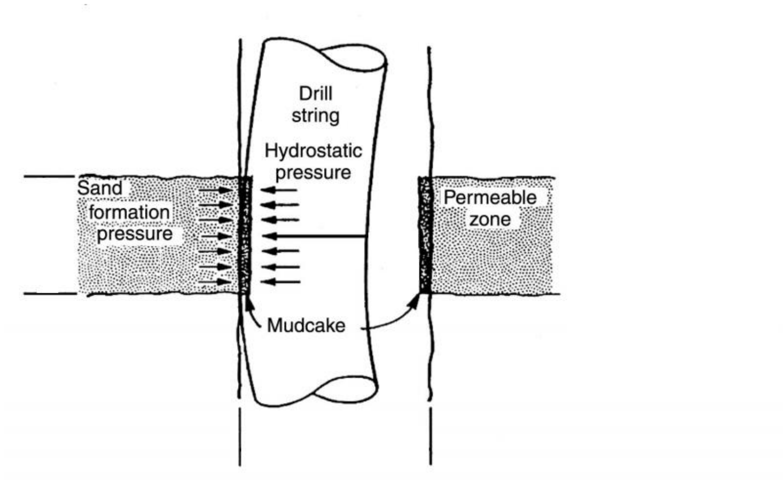


Figure V - Differential Sticking Mechanism.

- **Poor Hole Cleaning:** One of the main problems that drilling companies encounter while drilling is the hole cleaning. A proper hole cleaning via drilling mud is a must during drilling operations to reduce the unwanted cuttings in the circulating system as these cuttings have potential to resist in drill string rotation and movement. In a directional wellbore, cuttings tend to accumulate up in the high angle build section; this is why removing the cuttings from the hole is difficult. Improper hole cleaning also brings the risk of damaging downhole tools such as MWD tools and mud motors. However, if an MWD tool is employed on the drill string, cuttings intensity in the mud can be monitored by following the parameter called Equivalent Circulating Density (ECD), which is the apparent drilling fluid density. An increasing trend of ECD will imply accumulation of cuttings in the wellbore.

  In order to keep the wellbore clear of cuttings, correct mud properties should be used and slugs and sweeps should be pumped on a regular basis. Pipe rotation and flow rate would also help bringing the cuttings out of the hole. Conversely, poor hole cleaning will bring severe torque and drag problems [17], [19].

- **Wellbore Friction:** Since there is no frictional surface exists, technically it is impossible to eliminate torque and drag due to friction from the drill string.

Frictional forces arise opposite to direction of motion and are the main contributors for surface torque and drag. The severity of the acting side forces is determined by doglegs, tortuosity and wellbore profiles [17]. Furthermore, Aston et al, 1998 [20], claimed that frictional forces may result in the problems like twist-offs, wear, buckling and fatigue on the drill string or stuck pipe problem.

Wellbore friction is affected by two factors such as coefficient of friction between the contact forces (friction factor) and normal force between the tubular and wellbore.

Friction factor is defined as the measure of the degree of resistance to motion of two adjacent elements sliding against each other. It is the ratio of the frictional force to the normal contact force and affected by the drilling fluid and formation type. Friction factors must be assumed for open hole and cased hole according to previous drilling experience in corresponding formations and mud types for modeling. McCormick et al, 2012 [19] in his study claimed that in the oil industry, friction factors are generally lowered by using lubricants, co-polymer beads, mechanical friction reduction tools and proper hole cleaning which will result in torque and drag reduction. The opposing force to the side load against the borehole in the perpendicular direction is the normal force. It is a result of the influence of gravity and buoyancy on the drill string, elasticity of the drill string and effects of compression and tension on drill string acting upon wellbore profile [21]. Minimizing the normal force will be effective on proper weight transfer to the bit. Methods for reducing normal force are designing a well path carefully and using string components of lower weight [19].

- **Wellbore Tortuosity:** Weijermans et al, 2001[22], defined and studied wellbore tortuosity as another source of torque and drag. As directional wells become deeper and sophisticated, unwanted deviations from the pre-planned well trajectory occur frequently. Any unwanted deviation from the wellbore trajectory is regarded as wellbore tortuosity (Figure VI). It is a potential cause of additional torque and drag during drilling and well completions. Furthermore, productivity might even get affected due to high tortuosity.

There is no standard mathematical definition of tortuosity in the industry as it is evaluated based on the directional well plan and the survey of a well. It may occur any simple time due to formation effects and gravity acting upon the BHA and will result in an undesired inclination or azimuth change. While drilling with steerable bent housing motor systems, in order to keep up the line with the planned wellbore trajectory, directional drillers, after considering the survey received by the MWD tool, tend to steer the drill string according to plan. Collision avoidance considerations with the nearby wells would also need more sliding. All these effects will contribute to wellbore tortuosity.

On the other hand, with the introduction of technology called rotary steerable system (RSS), it is possible to automatically control the wellbore deviation in three-dimensional space, as with this technology it is possible to drill with continuous string rotation; hence, reduce the mechanical torque. Two-way communications from surface to downhole is provided with RSS technology and a continuous wellbore control is supported. This technology provides instantaneous corrections that result in drilling smoother curves. Accordingly, the contact loads between drill string and casing or open hole will be limited and frictional torque will be reduced.

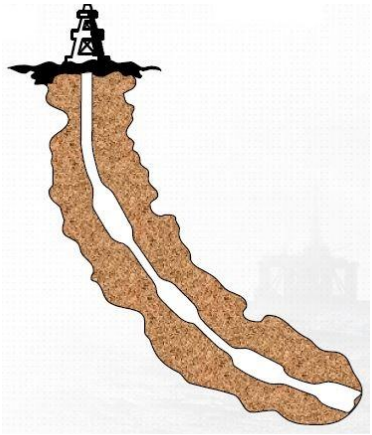


Figure VI - Wellbore Tortuosity.

2.1.3 Types

Torque types are studied well in the manual published by K&M Technology Group, 2003 [23]. Frictional torque, mechanical torque and bit torque are defined as the types of downhole torque observed. Categorizing torque components allows a better identification of friction for torque projections and allows proper measures for reduction techniques.

- **Frictional Torque:** Contact loads between the drill string and casing or open hole section of a well generates frictional torque. It is the only torque type generated while rotating off-bottom in a perfectly cleaned wellbore. The following parameters determine the magnitude of frictional torque.

    - **Tension/Compression in the Drill String:** Increasing tension in the drill string increases contact forces; hence, frictional torque. Tension is also effected by WOB, so is the frictional torque.

    - **String Weight:** As the string weight is increased, more weight is pushed at the side of the hole resulting in higher contact forces that yield to more frictional torque.

  - **Dogleg Severity:** A dogleg is the dramatic change of wellbore in three-dimensional space increasing the contact forces. This is generally a concern at shallower depths where the tension in the string is high. As the tension in the drill string gets lower deeper in the hole, the effects of dogleg severity become negligible.

  - **Inclination:** Higher inclination values yield larger component of drill string weight perpendicular to the borehole, increasing normal forces. Conversely, torque can decrease at very high inclinations, as more of the string weight is taken by the borehole wall; hence, decreasing the contact forces.

  - **Hole and Pipe Size:** The space between the drill string and hole is called annulus. A smaller annulus increases the effective stiffness of the pipe and increase contact forces.

  - **Lubricity & Friction Factor:** Lubricity controls friction and it is controlled by the drilling fluid and formation type. During drilling in abrasive formations, significant torque changes can be seen.

- **Mechanical Torque:** Interaction of cutting beds, unstable formations and differential sticking with drill string and/or BHA components generates the mechanical torque.

  - **Cutting Beds:** Mechanical torque will be observed in a wellbore that is filled with cutting beds. A better hole cleaning is necessary to prevent mechanical torques due to cutting beds.

  - **Unstable Formations:** Sloughing and swelling formations increase mechanical torque. Proper drilling fluid parameters should be in place for a better borehole wall.

    - **Differential Sticking:** A differential stuck must be avoided, as it is the condition of being unable to rotate or move the drill string resulting in mechanical torque.

- **Bit Torque:** The direct result of interaction between the formation being drilled and the drilling bit is the bit torque. Payne and Abbasian, 1997 [24], claimed that actual bit torques change dynamically and substantially during drilling. They demonstrated the factors influencing bit torque as WOB, RPM, formation characteristics, PDC bit design variations, bit wear and hydraulics. PDC bits often have higher torques compared to roller cone bits.

Types of drag can simply be classified into two as upward and downward drag occurring in the opposite direction of string movement relative to the wellbore [24]. Most of the drilling rigs have a weight indicator that shows instantaneous string weight, WOB, drag and overpull forces [23]. The force observed on the drilling line includes the weights of the travelling block and TDS equipment. Therefore, while computing the string weight, it is necessary to subtract the weight of traveling equipment from the total load to analyze drag forces while tripping in or out.

2.1.4 Challenges

Although drilling with a BHA of RSS consists eliminating most of the torque and drag problems, not all of the directional wells are drilled by RSS for particular reasons. RSS are limited with the DLS that can be achieved as compared to the wellbore geometries in which DLS is greater and easier to be achieved when the motor in use is a conventional in kind. Those directional wells that are not drilled with RSS have to be drilled with a downhole motor – MWD System that brings challenges associated with torque and drag.

Torque at the bit increases with increasing weight on the bit. Bit torque is proportional to the tangential force vector to bit rotation to the right. Therefore, the downhole motor with bent housing experiences an equal force to the left that is called the reactive torque.

Tool face responds to the changes in bit weight due to the relationship between bit weight, bit torque and tool face orientation.

During the change of drilling mode from rotary to slide drilling with a downhole motor, the driller normally stops drilling, pulls the drill string up, and turns the drill string to release torque. Then he must re-orient the tool face considering the reactive torque on the bit and control the slack off at the surface to accomplish desired tool face angle. Challenges also increase with increasing wellbore drag [23].

- **Weight Transfer to Bit:** Weight transfer to the bit is achieved by slacking off at the surface or pushing down. Drag force is the difference between the actual weight available at the bit and the amount slacked off at the surface and is opposed to the pipe movement. Controlling the weight on the bit becomes difficult as depth or horizontal displacement increases because of the elasticity of pipes. The elasticity will cause a part of the pipes to move while other parts are stationary or move with different velocities. Sometimes weight is released suddenly because of difference between kinematic and static friction between drill string and casing or open hole. Hang-ups such as key seats, ledges and uneven cutting beds also contribute to the sudden release of bit.

  The bit rotation will suddenly stop if a sudden weight transfer is released from the drill string that exceeds the maximum weight that motor can withstand. Such condition is called a motor stall and it is destructive for the rubber component of the motor.

  The longitudinal drag of drill string increases with increasing horizontal departure of a well. Hence, weight transfer to the bit without stalling motor becomes more difficult and drilling becomes more challenging.

- **Tool Face Orientation:** Tool face is the reference used for orienting the wellbore in the desired well path. Orientation of tool face become more challenging as horizontal departure of a well increases due to the difficulty in releasing torque from drill string during initial reciprocations. Additionally, reaching to the bottom smoothly becomes more challenging. Orientation of tool face is a widely encountered problem that drillers face as it is difficult to achieve without stalling the motor.

- **Tool Face Angle Maintenance:** Maintaining the tool face orientation with the increasing horizontal departure is also as difficult as achieving the desired tool face orientation as available weight on the bit oscillates; hence, affecting the reactive torque and changing the tool face angle.

- **Stick Slip Phenomena:** Stick slip is defined as non-uniform bit rotation in which the bit stops momentarily at regular intervals which results the string to torque up and then spin free. Stick slip is usually encountered in high angle wells with aggressive PDC bits and high WOB when the downhole frictional torque exceeds the rotary torque. It is detected by MWD tool downhole. High stick slip will yield to bit damage, low ROP, connection overtorque, drill string twist-off and back off. It can be reduced by increasing RPM decreasing WOB.

Occurrence of drag in the drill string also brings another challenge called buckling which needs detailed explanation.

- **Buckling:** Deformation of rectilinear of a tubular due to axial compression load is defined as buckling [25]. As mentioned in K&M Manual [23], it is not easily detected and yields to unnecessary wiper trips, bit changes, mud property changes where buckling is the real problem. It is generally encountered in slide drilling or liner running in high angle holes, deepwater ERD wells where long casing strings are used, drill pipe compression during hole size enlargement and in completions where compression is necessary to stab into liners. The pipe that is buckled will quickly be fatigued when rotated.

Buckling occurs due to compressional forces in the drill string. Compression is build up by drag forces in the drill string until critical buckling load is overcome and buckling is observed. However, if an RSS is used, the effects of drag forces and compression will be minimized by continuous rotation. It is still possible to cause buckling while drilling vertical with rotation; although, it is unusual to get the rotating pipe buckled drilling high angle well as it is difficult to apply enough WOB. There are two types of buckling namely, sinusoidal and helical buckling.

- **Sinusoidal Buckling:** Sinusoidal or snaky buckling occurs while the drill string is under compression as it starts to snake in the borehole (Figure VII). It brings about the problems related to weight transfer to the bit. Weight can be transferred by pushing the drill string by applying more weight; however, the drill string will become snakier in the wellbore. As the buckling increases, weight transfer will become more problematic. Sliding drilling with a PDC bit with a downhole motor will be more difficult once sinusoidal buckling is observed. With the improper weight transfer to the bit, the bit will start to bounce on bottom yielding to motor stalls and lose of tool face orientation. Under these circumstances, a roller cone bit might be of better choice. It might also be possible to minimize the effects of buckling with an optimized BHA and bit design.

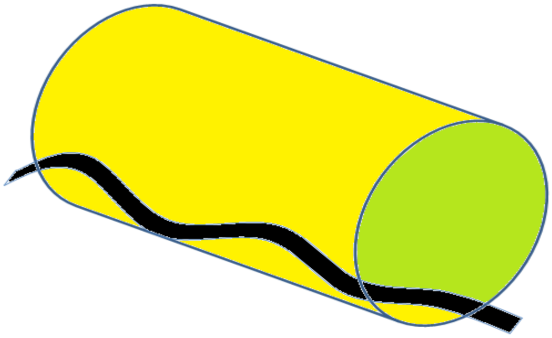


Figure VII - Sinusoidal Buckling.

- **Helical Buckling:** An immediate change of drill string shape from sinusoidal to coiled spring shape brings helical buckling (Figure VIII). As the drill string is coiled in helical buckling, no further downward movement is possible. As a result, no further weight transfer to the bit possible, as the coiled drill string will grip the wellbore better with more weight applied at the surface. Therefore, the drill string design must be done adequately to prevent helical buckling while tripping, liner running operations and slide drilling with a downhole motor.

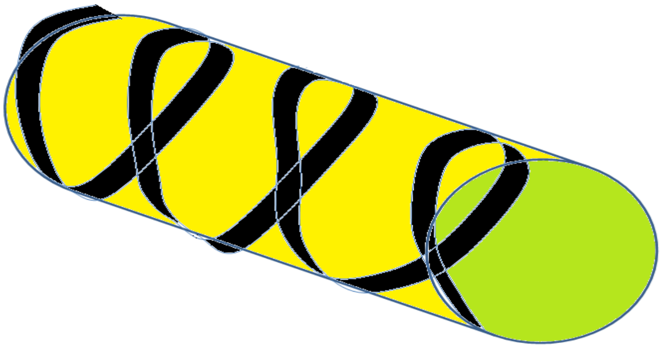


Figure VIII - Helical Buckling.

It is important to make the well path design with buckling phenomenon in mind. It can be prevented by placing HWDP in particular intervals in the drill string to provide more stiffness to the drill string as HWDP does not contribute to torque and drag on vertical-to-horizontal well and easily helps to prevent buckling. However, in ERD wells they will bring torque and drag problems. It can also be prevented by using special downhole tools such as bladed drillpipe, non-rotating drillpipe protectors and roller centralizers. However, using of these tools is expensive and other risks such as lost in hole are possible. The best defense against pipe buckling is continuous rotation that the RSS provides.

2.1.5 Reduction Techniques

Drilling deeper and complex trajectories has become a common application for reaching a number of different production zones from the same location to reduce the costs.

However, increasing demand to drill directional wells brings new challenges and aspects including torque and drag. It is important to understand these challenges in order to reduce or prevent torque and drag problems and finalize drilling operations successfully [25].

- **Drill pipe Limitation**: Drill pipes have to be able to handle the torque occurring in the wellbore during rotary drilling. The critical point on the drill string is expressed to be the point where the maximum torque is occurred. During drilling, if critical point is able to handle the maximum torque, so as the rest of the drill string. In addition, drill pipes should be designed to handle the axial tension compression forces and side loads. Accordingly, modeling is very important during planning stage of a well to predict the forces during drilling. Design of drill string is critical in torque management. In order to reduce the drill string weight, tapered drill pipes can be chosen.

- **Topdrive Limitation**: Surface torque necessary to drill conveniently in deep wells is usually found to be higher than the top drive capacity. Therefore, surface torque reduction is necessary to reach target depth.

- **Hookload Limitation**: Drawworks capacity determines how much weight can be suspended on the hookload and it should be able to handle the weight of the drill string in the drilling fluid. It should also be capable of handling friction forces occurring while pulling out of hole. Surface torque and pick up weight both depend on the friction factors and drill string weight. Surface torque increases with increasing pick up weight. Consequently, the pickup weight will be kept down with keeping surface torque below a certain value.

- **WOB Control**: WOB is negatively affected by the wellbore tortuosity. High stick slip, axial and lateral vibrations may also occur due to irregular WOB. These may result in drill string failures. However, drilling a smooth wellbore helps overcoming drag forces and WOB transfer effectively. In addition, increasing the drill string RPM also helps to overcome drag forces but brings about high surface torque.

- **Casing Wear**: Casing wear is usually a problem in deep wells due to rotational torque. The casing is subject to more rotational friction because of the side forces and casing wear is faster. Excessive casing wear can result in a need of using casing patchers, liners or entire casing string replacements that will increase costs.

- **Directional Control**: Rotation of the drill string has to be completely stopped to change the direction of the well during drilling with a steerable motor. The tool face has to be oriented in the desired direction and driller has to start sliding. The driller has to stop drilling, come off bottom and release the trapped torque by reciprocating in order to change from rotary drilling to sliding. This operation is difficult when there is high friction resistance and tortuosity in the wellbore and while drilling with aggressive bits.

- **Room for Safety**: There are several factors to be considered which are related with torque at the time of well planning such as: topdrive and hookload capacities and pipe yield strength. The pipe strength should be designed to overcome torque and drag, and the hookload and topdrive capacities should be higher than the forces expected from the drilling operations to leave room for safety. Operating the drilling systems in maximum capacity will bring about the risks of failure.

Torque and drag reduction process is a composition of many different methods. One method does not usually solve the problems alone. In order to reduce torque and drag, below mentioned methods might have to be employed at the same time.

- **Optimized Well Plan**: Surface torque is mostly generated by the wellbore profile. Most of the time engineers may be able to develop alternative trajectories to reach the target zone with reduced surface torque while drilling. Even small changes in the directional plan may result in torque reductions. Several options are available to make a new well plan by changing build rate, turn rate and dogleg severity. The best way to foresee and eliminate torque and drag problems is the optimized well planning.

- **Bit Selection**: Selection of bit with considering different drilling purposes is important in order to maintain a good hole quality. Selection criterions are usually ROP, steerability, durability and vibration management. It is highly possible for a short gauge bit to result in wellbore tortuosity and high caliper variations due to its aggressiveness. Therefore, tortuosity caused by bit properties should be eliminated as it increases drag forces.

- **Drill String Design**: Surface torque is directly proportional to string weight and a decrease in drill string weight may provide a considerable reduction in surface torque. The drill string weight can be optimized with less use of HWDP and DC without affecting WOB to drill effectively. It is an important and difficult practice to find the right balance between torque, drag, hydraulics and rig mechanical limits while performing drill string design.

- **Use of Rotary Steerable System**: Use of steerable motors for directional control creates more tortuosity compared to RSS as this type of tool has an angle of kick-off (AKO) which is set at surface prior to drilling and cannot be changed once the tool is at downhole. The motor is steerable by the AKO setting and driller has to stop rotation to slide and orient the wellbore as desired. This application creates ledges in the wellbore by applying non-constant DLS. However, it is easy to maintain a smoother hole trajectory and have less tortuosity with use of rotary steerable system. Drilling a smoother wellbore minimizes the torque and drag problems. RSS provides the automatic correction of drilling direction with non-stop string rotation and hence; the best system to follow the desired directional plan and it accounts for a better casing run and completions. Using RSS might reduce the surface torque up to 15%.

- **Use of Modular Motor**: Surface torque increases with increasing RPM but using a modular motor may further reduce it. A modular motor can be a part of RSS internal communication system. With use of modular motor in the RSS, string revolution can be minimized; therefore, wellbore torque is also minimized while revolution at the bit is maintained. Reducing the string revolution also helps the topdrive to be safe from overheating or encounter mechanical problems and decreasing non-productive time. Modular motor also helps to increase the rate of penetration.

- **Use of Non-rotating Drillpipe Protectors**: Metal-to-metal contact in the wellbore between drillpipe tool joints and casings can be prevented by using non-rotating drillpipe protectors (NRDPP) that reduce the torque and casing wear. NRDPP help drillpipes to rotate within the protector, while bearing sleeve is stable. The decrease in effective size where the friction occurs reduces the torque. The new and less coefficient of friction between the sleeve and polished metal surface of the sub also reduces the torque.

- **Use of Mud Additives**: The best way to reduce surface torque is the use of oil based or synthetic based drilling fluid rather than water based mud. However, it is also possible to generate lower surface torque and drag by reducing friction factors by adding mud additives to water based mud. It is possible to reduce the torque up to 25% by adding correct mud additives. The selection of mud type whether oil based or water based depends on the economical considerations.

- **Proper Hole Cleaning**: If cuttings are not properly transported to surface from downhole, they will accumulate in the wellbore and increase frictional resistance that will result in higher torque and drag. It is very important to achieve correct properties in the mud for better hole cleaning. Slugs and sweeps should be pumped and circulation must be performed regularly to maintain the hole clean of cuttings.

2.2 Review of Previous Torque and Drag Models

A torque and drag model is generally used during the well planning stage to confirm whether the proposed well path can be drilled and completed or not. It is also used to monitor torque and drag values in real time and take precautions and apply prevention techniques once the values exceed the allowable limits.

There had been many research conducted previously to develop an accurate model for torque and drag calculations. These studies are mainly based on Soft String Model and Stiff String Model to calculate torque and drag values in a wellbore. Soft String Model is the common model used in the industry; whereas, the Stiff String Model is hard to apply and there is no available industry formulation.

2.2.1 Soft String Model

Johancsik et al., 1984 [23], developed the Soft String Model as a model for directional wells that ignores any tubular stiffness effects and considered the drill string consisted of soft components with weight. The string is treated as a heavy cable along the wellbore that means contact forces are supported by the wellbore and torque forces and axial tension are supported by the string. For the practical applications of this model, friction coefficient determination is critical.

Mason and Chen, 2007 [26], studied that Soft String Model assumes the loads on the drill string result only from the effects of gravity and frictional drag occurring due to the contact between the wellbore and drill string. The product of normal force between the wellbore and drill string and the friction coefficient yields to the frictional force.

The normal force, F_n, equation is shown on equation 1:

$$F_n = \sqrt{(F_t \Delta\phi sin\theta)^2 + (F_t \Delta\phi W sin\theta)^2} \tag{1}$$

where,

F_t	is the tension force at the lower end of the string element.
$\Delta\phi$	is the change in azimuth angle over the string element.
θ	is the inclination at the lower end of the string element.
W	is the buoyed weight of the string element.

The change in tension and torque are calculated by equations 2 and 3 after the normal force calculation:

$$\Delta T = W cos\theta \pm \mu F_n \tag{2}$$

$$\Delta M = \mu F_n R \tag{3}$$

where,

ΔT	is the increment in tension across the string element.
ΔM	is the increment in torque across the string element.
μ	is coefficient of friction between the string and wellbore.
R	is the radius of the string element.

All the Soft String Torque and Drag Models assume that the drill string is consisted of short elements joined by connections that transmit torsion, tension and compression but not the bending moment. The basic equations of friction are applied to each segment with calculations starting from the bottom of the drill string and continuing upward to the surface. Each short interval of drill string contributes increments of torque, drag and weight. Forces and torque values are added to produce the cumulative loads on the string. Initial conditions are specified at the bit and the inputs would be weight on bit and bit torque values for drilling operations.

The most important assumption is that the drill string is in continuous contact with the wellbore from bottom to the top that means that radial clearance effects are ignored and the bending moment is not considered in Soft String Model.

2.2.2 Stiff String Model

Mason and Chen, 2007 [26], mentioned that a Stiff String Model should consider string bending stiffness and radial clearance between the drill string and wellbore by taking into account that certain parts of the drill string are not in contact with the wellbore. As stiff tubular are forced around deviated sections, higher sidewall forces occur and as the pipe straightens, less side forces occur. Variation of contact area between wellbore and a string component will also occur. A Stiff String Model must consider concentrated bending moments at drill pipe connections, stabilizers and casing centralizers. Overall, a Stiff String Model is designed to be a more realistic approach taking into account stresses and loads acting upon the string and borehole wall.

Stiff String Models are declared to be more relevant for the following situations:

- Well designs with narrow radial clearances.
- Well designs with highly tortuous trajectories.
- Well paths of very high DLS.
- Casing running with stiff tubular.

A great variety of numerical methods is necessary to generate a Stiff String Model which makes is more complex to solve compared to Soft String Models. There have been many Stiff String Models developed, but there is no industry standard formulation that makes the model impractical.

CHAPTER 3

THEORY

3.1 Torque

Torque (the moment of force) is the ability of a force to rotate an object about an axis. Torque is described as the cross product of the lever-arm distance vector and the force vector, which tends to produce rotation [27].

Basically, torque is a measure of the turning force on an object. A daily life example is the handle of a wrench connected to a nut to loosen or tighten it by pushing or pulling. The force applied to turn the nut is the torque, the turning force.

The symbol used for torque is the Greek letter τ, pronounced as "tau".

The measure of torque depends on three varieties such as, the force applied, the length of the lever arm connecting the axis to the point of force application and the angle between the force vector and the lever arm. The formula of torque is defined by equations 4 and 5:

$$\tau = r\ x\ F \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

$$\tau = ||r||\ ||F||\ sin\theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

where,

τ	is the torque.
r	is the vector of displacement.
F	is the force vector.
θ	is the angle between the force vector and the lever arm vector

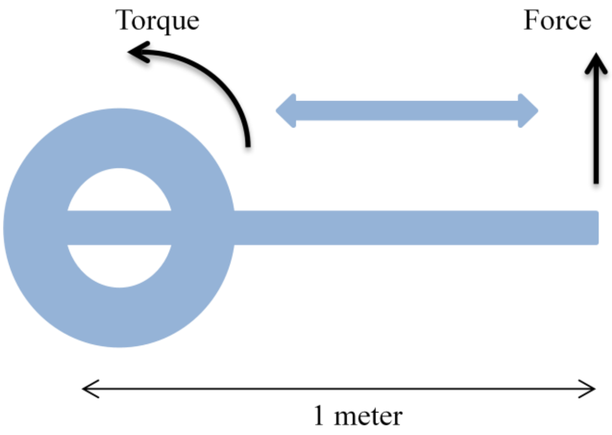


Figure IX - Torque on a Wrench.

Figure IX demonstrates the torque on a torque wrench. On the demonstration, a force applied upwards from a distance of 1 meter causing the wrench to rotate counter-clockwise is shown. The torque applied here is the force (newton) multiplied by 1 meter. As the force is applied vertically to the torque wrench's axis, the angle θ equals 90°, and (sin90°) is equal to 1.

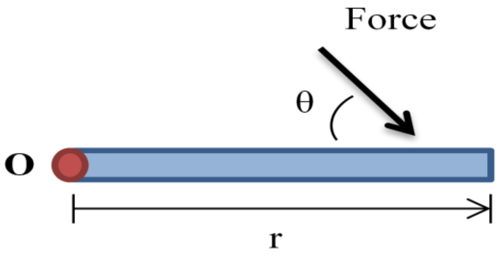


Figure X - Force Applied Non-Vertically.

The torque applied on the point O on Figure X is the multiplication of force applied (F), distance (r) and the sinθ value. The angle θ here is below 90°, assume 30°. Value of (sin30°) equals 0.5. Hence, the torque applied here will be the half value of torque in which the force applied vertically. Torque reaches the maximum value when the force is applied with 90°. The value of torque decreases with the angle approaching 0° as sin0° equals 0. The force applied with 0° angle (horizontally) has no effect on rotating the wrench.

The SI unit of torque is newton-meter (N.m), oil industry generally uses the pound-foot (lb.ft) unit. 1 newton-meter approximately equals to 0.7376 pound-feet.

3.2 Drag

In physics, drag is defined as the force that appears opposite to the direction of motion due to resistance of surface, i.e. friction. Drag forces always decrease the velocity of a moving object.

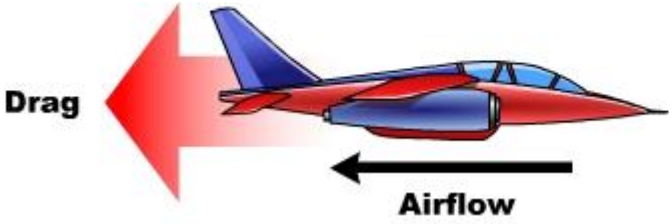


Figure XI - Drag, Occuring Opposite to the Direction of Motion [31].

Drag force on an airplane is shown on Figure XI. On airplane, drag force occurred due to resistance of air on the surface of airplane and slows it down.

Oil industry considers the drag as a force that increases or decreases the weight of the drill string. The visual weight of the drill string on surface is either heavier or lighter depending on the direction of the drill string motion. If the drill string is being run in the hole, the direction of drag force is from the bottom to the surface; hence, visual weight of the drill string is lower than what actually it is. If the drill string is being pulled out of hole, the direction of drag force is downwards; hence, visual weight of the drill string is higher than what it actually is.

Drag on the drill string in a directional well can easily be calculated by subtracting the apparent weight from the actual weight. If the pipe motion is downwards, the drag is negative (-), reducing the drill string weight. If the pipe motion is upwards, apparent drill string weight is the sum of drag force and the string weight; hence the drag force is positive (+).

3.3 Torque and Drag in Deviated Wells

Torque and Drag in deviated wells are the two important parameters that have to be taken into account to design well paths and modify the drilling parameters like WOB, RPM etc. As torque and drag appear due to contact between the drill string and formation, normally in vertical wells there is no such concern because the contact between drill string and formation is very little (negligible). However, in a deviated well, torque and drag are assumed to be caused entirely by friction forces that result from the drill string and wellbore contact.

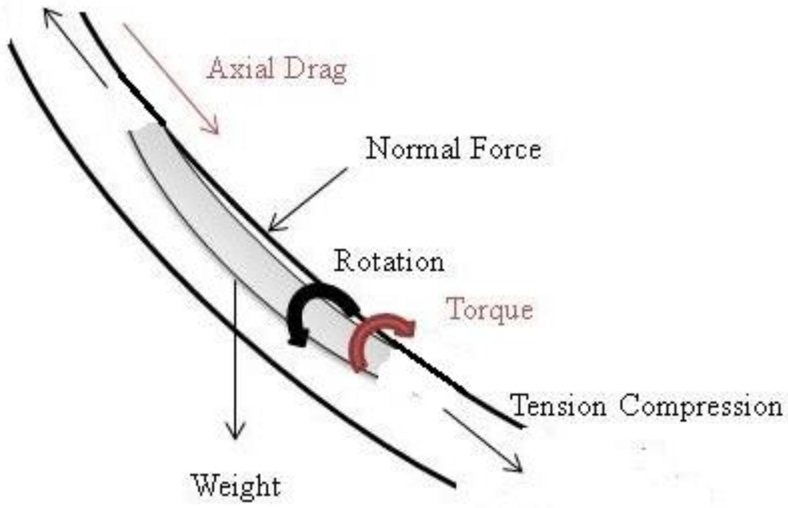


Figure XII - Forces Acting on a Drill String.

Figure XII shows the forces acting on a drill string while the direction of motion is upwards. The direction of axial drag is downwards as it occurs in the opposite direction of pipe motion. The direction of rotation is clockwise looking downhole; hence, torque generated is counter-clockwise. The weight of drill string component is parallel to the gravity. The normal force is the effect of gravity on the pipe. In order to calculate torque and drag values, the normal force has to be calculated first. Tensional force occurs at the lower part of the drill string component. The coefficient of friction is also highly important and depends on surfaces, drill string and wellbore. The product of normal force and coefficient factor represents the magnitude of friction force [23].

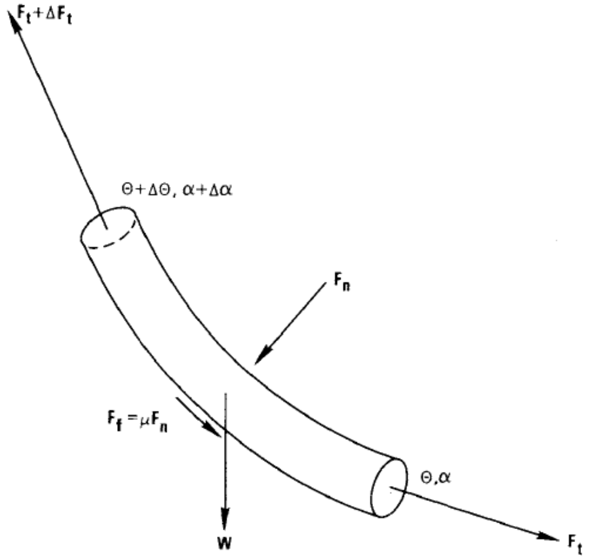


Figure XIII - Forces Acting on a Bended Drill String Component.

Figure XIII shows the forces acting on a bended drill string component in a directional well. The normal force F_n is the negative vector sum of components from the weight W and from the tension forces F_t and $(F_t+\Delta F_t)$. In order to calculate the frictional force, it is only necessary to know about the magnitude of the normal force, not the direction of it.

The magnitude of the normal force is calculated via equation 1:

$$F_n = \sqrt{(F_t \Delta\phi sin\theta)^2 + (F_t \Delta\phi W sin\theta)^2} \tag{1}$$

where,

F_t	is the tension force at the lower end of the string element.
$\Delta\phi$	is the change in azimuth angle over the string element.
θ	is the inclination at the lower end of the string element.
W	is the buoyed weight of the string element.

Once the normal force is calculated, the tensional force can be calculated:

$$\Delta T = W cos\theta \pm \mu F_n \tag{2}$$

where,

ΔT	is the increment in tension across the string element.
μ	is coefficient of friction between the string and wellbore.

The minus or plus sign on this equation allows for pipe motion, i.e. upwards or downwards. If the pipe motion is upwards, plus sign will be used in the formula and vice versa.

Finally, the torsion element can be calculated:

$$\Delta M = \mu F_n R \tag{3}$$

where,

ΔM	is the increment in torque across the string element.
R	is the radius of the string element.

These equations would be accurate once applied to small elements of the drill string. If longer elements are used, small errors will occur. For instance, an assumption for the normal force equation is that the tension at the bottom of the element is calculated and is the same over the length of the element to the top. Therefore, second-order terms are neglected due to complexity, as there is no solution exists for predicting the drill string drag that is a three-dimensional belt friction problem with gravity.

If torque and drag are to be calculated using these formulas, the drill string elements should be small for the errors to be small. The best and easiest way to choose the drill string element length is to basically use the survey data that generally consists of 100 ft (30 m) increments. Whenever an intermediate point torque and drag values are desired, a linear interpolation can be made.

In order to determine whether the calculated torque and drag values do not pose a threat to drilling operations, the yield strength (tension limit) tables for different steel types are used. A drill string design must be performed prior to drilling operations. Torque and drag compression loads in the drill string must be compared with torsional, tension and buckling capabilities of the tool joints and drill string components.

3.4 Torque and Drag Consideration in Drill String Design

G.K. McKown states in his article [28] that an optimum drill string design requires a clear understanding of the required functions that the drill string has to serve and the importance of each function. A drill string design has to facilitate three basic functions:

- Transmit and support axial loads.
- Transmit and support torsional loads.
- Transmit hydraulics.

A well design is performed based on the well objectives and the likeliness of accomplishing the objectives. Rotary steerable systems have increased the drilling efficiency; hence, the probability of achieving the planned well design in higher angle and longer reach wells. Major constraints to drilling these types of wells are torque and drag because the contact between wellbore and drill string increases with well angle and with horizontal distance. Drill string design becomes a major consideration due to high torsional and tensile load requirements and downward movement. S-shaped wells, higher kick-off points and higher hole curvatures increase torque and drag. As this is undesirable, a well design with lower torque and drag is always more attractive.

Excessive torque usually is associated with excessive drag. However, a well design may produce lower torque while producing higher drag and vice versa compared to other well design options. The selection of the well design considering the torque and drag analysis may require some compromise.

It is critical to know about the condition and strength of drill string components during the design process. Strength limitations are effected by wear of the component and previous use. Wear and strength can be determined by visual inspection and measurements but determining the fatigue life is difficult for the majority of used drill string components.

The fatigue limits of drill string components that are used in high angle wells are critical due to the high bending stresses occurring in the areas of angle and direction changes and in regions where compressive loads are sufficient to cause buckling. As the drill string components in high angle wells will be pushed to the limits as the well is being drilled, premium components must be the first choice. Limitations for all the drill string components should be known before the drill string design to identify special requirements and specifications to be placed on component selection. In addition, the safety factors to be used in drill string design should be chosen to account for wear and component strength reduction.

Drill string design flowchart is demonstrated in Appendix A.

3.5 Friction Factor

In order to ensure a realistic approach to torque and drag calculations, friction factors should be considered carefully. This allows the drill string design to overcome increased torsional and axial loads generated by friction and are not over-engineered.

Although the friction factor values are well established for certain formations, it is appropriate to use higher values in order to account a safety margin for unexpected situations like wellbore shape, stuck-pipe problems and swelling/sticky formations.

Actual friction coefficient values are effected by mud type, formation type and casing points. These values are generally known before the drill string design process and can be used for torque and drag analysis. The values should be selected for the worst cases to provide a safety margin for unpredictable conditions. Using the data from an offset well is reasonable.

3.6 Torque and Drag Real Time Measurement

Azar, 2007 [32] mentioned that predicted and actual torque and drag versus depth log should be maintained during drilling operations which enables the friction factors to be updated and verified. Enabling the actual and predicted friction factors comparison, prediction and prevention of problems are possible with such a log instead of dealing with after the fact.

The log can also show the effect of changing the bit types or changing operational parameters. As demonstrated on Figure XIV, a PDC bit might result in an increase in torque values compared to roller cone bit.

Deteriorating hole conditions can also be identified by this log such as doglegs, cuttings accumulation and local hole features. Cuttings buildup effects on torque can also be seen on Figure XIV.

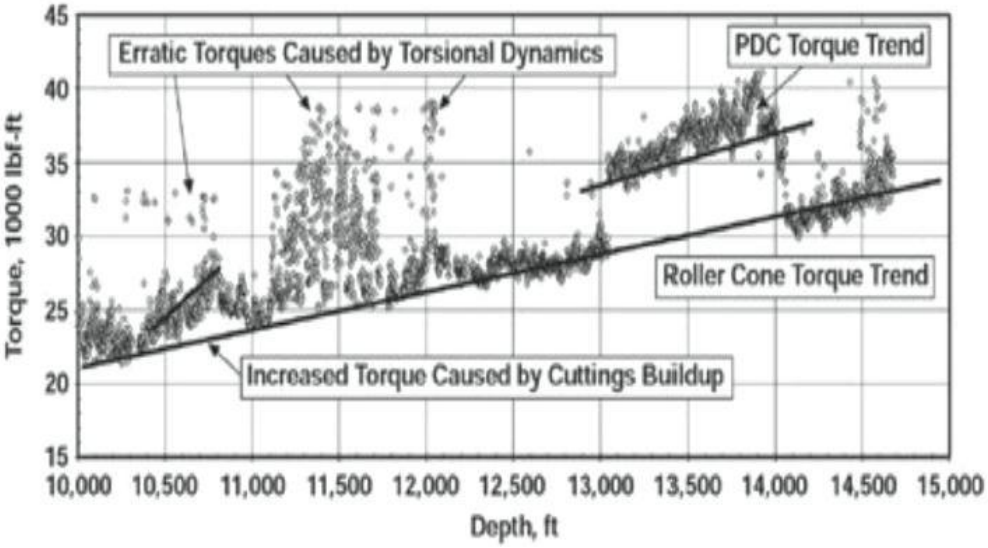


Figure XIV - Log of Actual vs. Predicted Drill String Torque [32].

3.7 Special Drill String Components

Directional drilling industry uses the heavy wall drill pipe to reduce the likelihood of damage due to buckling in high compressive load regions. Compressive service drill pipe may be used where heavier drill string components create excess torque and drag.

Compressive service drill pipe can be conventional drill pipe with wear protector attached (evenly spaced) on it or a specially made pipe with integral upsets which reduces the stress restricting lateral movement of the pipe joint when buckled. Integral upsets reduce the stress also in high angle changes.

Aluminum drill pipe is frequently used where torque and drag loads are excess for conventional steel components. Aluminum drill pipe placed in the high angle areas significantly reduces torque and drag.

In order to reduce casing and drill pipe wear, drill pipe protectors, rubber or steel, may be used. Casing and drill pipe wear are expected in high angle wells due to higher contact forces between the wellbore and drill string elements. In addition to reducing wear, drill pipe protectors also reduce fatigue of drill pipes during the rotation in angle changes and doglegs. Rubber protectors can also reduce frictional drag.

CHAPTER 4

STATEMENT OF THE PROBLEM

Drilling for oil, gas or geothermal wells is an expensive business. Mostly, special and expensive equipment and technology are involved in drilling operations. Experienced personnel are required for the drilling activities of complex wells such as HPHT, and horizontals. Therefore, the operating companies desire to finish and complete their wells with minimum NPT and minimum cost. In order to accomplish that, they must take correct precautions and decisions prior to and during drilling.

One of the factors that generally result in NPT occurrences is torque and drag generated in the wellbore during drilling. Miscalculated and/or misinterpreted values result in equipment and time loss that would yield to undesired consequences.

The motivation behind conducting this research is to assist drilling field personnel to make quick calculations for the torque and drag analysis while drilling directional and horizontal wells. Industry needs easily accessible tools for the torque and drag calculations, so that the field personnel can make quick and reliable calculations. It is observed that field personnel are lacking the details of torque and drag theory and are not able to make quick calculations regarding whether the ongoing drilling process is following the torque and drag limitations.

Furthermore, the findings of torque and drag calculations during the well path design process could reveal possible risks and prevent the problems before they happen. The well path can be designed in such a way that torque and drag related problems are minimized and desired target reservoirs are effectively hit.

Finally, in case of applying unplanned operations or updating the wellbore trajectory, the equipment that is going to be needed or drilling parameters need to be applied could be identified in a practical manner by using the findings of torque and drag calculations.

Torque magnitudes are required to be calculated for complete interval of the wellbore as opposed to a single depth torque magnitude. This way the field personnel can have an idea of what torque and drag trend to expect in the course of drilling at any depth of the wellbore section in subject.

CHAPTER 5

CONSTRUCTION OF THE TORQUE AND DRAG MODEL

In this study, Soft String Model [23] is used to calculate frictional torque, a result of contact between wellbore and drill string. Several parameters such as drill string, casing, formation types, drill string unit weight, buoyancy factor and buoyed weight, well inclination and azimuth and friction coefficients have to be considered to employ Soft String Model to calculate the normal force and eventually torque and drag by assuming the average rotational torque.

5.1 Calculation Methodology

Figure XV gives the representative calculation methodology of the wellbore bottom hole assembly (BHA) items. The BHA items are taken to be calculated at 3.28 ft (or 1 m) intervals. The azimuth and hole deviation along each and every 3.28 ft is interpolated accordingly and used in calculation for each segment.

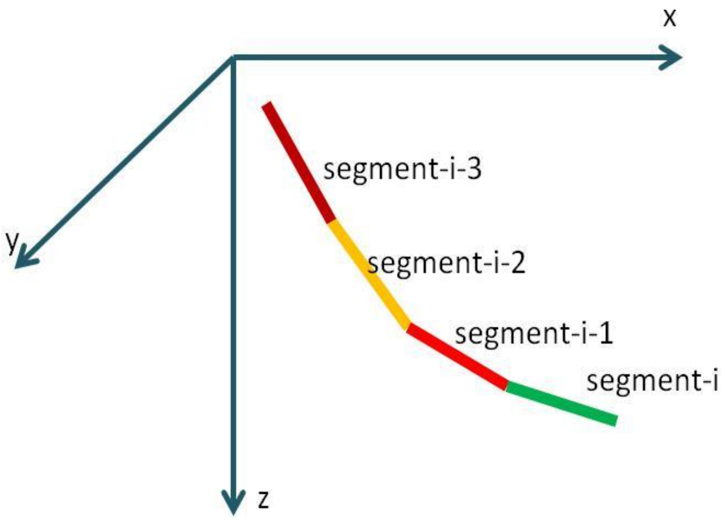


Figure XV - Calculation Methodology.

5.2 Drill String

Kök [29] declares that the drill string is the connection between the rig and the drill bit and drill string design is very important for rotary drilling. Drill string serves to several purposes including the drilling fluid transfer to the bit, transfer rotary motion to the bit, transfer weight to be set on the bit, provide upward and downward motion of the bit and stabilize the bottom-hole assembly to minimize downhole vibrations.

Drill string consists of drill pipe and BHA. The drill pipe contains conventional drill pipe, heavyweight drill pipe and sometimes a reamer. BHA frequently contains drill collars, stabilizers, jars, reamers, shock subs, bit and bit sub. MWD tools, DST tools and junk baskets might also be included in drill string.

The drill string that is designed to drill a well is inserted into the model manually in order to get accurate torque and drag calculations and results.

Appendix-B gives the OD, Nominal Weight, Grade-Upset Type, Torsional Yield Strength and Tensile Yield Strength of common drill pipes in use of the industry.

5.3 Casing

In order to reach the target depth, drilling operations often need casing strings [29]. Casing is the large diameter pipe that is run into a drilled section of a well and held into place with cement. Several types of casing string types exists like conductor casing, surface casing, intermediate casing, liner, etc. to serve purposes like preventing contamination of fresh water well zones, preventing upper formations from breaking down, isolating different zones, sealing off high pressure zones, preventing fluid loss, providing a safe wellbore for production equipment setting.

Casing points and cased hole sections must be carefully modeled for accurate torque and drag calculations and results.

5.4 Formation Types

Different formations have different properties. For torque and drag calculations, friction factors are dependent on formation types. Friction factor to be used in torque and drag calculations should be identified according to formation types.

5.5 Unit Weight

Unit weight has to be calculated for each drill string section for accurate cumulative torque and drag calculations. Since the drill string consists of pipes, outer and inner diameters are important for the calculations. It is calculated as:

$$W_{unit} = \pi \frac{OD^2 - ID^2}{4} \quad \text{.........(6)}$$

where,

OD is the outer diameter of the pipe.
ID is the inside diameter of the pipe.

An accurate calculation with the unit conversions is:

$$W_{unit} = 65.5 \frac{\text{lbs}}{\text{gal}} \text{ x } \frac{\pi}{4}(OD^2 - ID^2)(in^2) \text{x 1 ft x } \frac{\text{1 gal}}{231 in^2} \text{ x } \frac{\text{12 in}}{\text{1 ft}} \text{ x} \frac{1}{\text{1 ft}}$$

which will finally yield to the unit lbs/ft and is used in the model:

$$W_{unit} = 2.67\ x\ (OD^2 - ID^2) \quad \text{.........(7)}$$

5.6 Buoyancy Factor and Buoyed Weight

Buoyancy is the upward force that keeps the things floating on the fluid. This upward force makes the objects lighter when they sink or float on the fluid [30].

In a drilling environment, the object is the drill string and the fluid is the drilling mud. Drill string weight should be calculated in the mud and drilling designs should be made accordingly as the string will weigh less in the mud. The weight of drill string in the mud is the buoyed weight.

Buoyancy factor is calculated as:

$$BF = \frac{65.5-\rho}{65.5} \quad \text{...(8)}$$

where,

ρ is the mud weight, ppg.
65.5 is the density of steel, ppg.

Mud density is important for buoyancy factor calculations. The unit of mud density is pounds per gallon. If the density is known in the unit of specific gravity, this has to be multiplied by the constant 8.33 to convert ppg.

$$\rho_{(ppg)} = \rho_{(SG)} x\ 8.33 \quad \text{...(9)}$$

Then, buoyed weight can be calculated after the buoyancy factor calculation:

$$Buoyed\ Weight = Actual\ Weight\ x\ BF \quad \text{...(10)}$$

The weight used in the torque and drag model is the buoyed weight.

5.7 Well Inclination and Azimuth

Inclination and azimuth are the two important parameters for Soft String Model. During drilling operations, these parameters are generally measured during directional surveys that are performed at approximately every 30 meters (100 ft.) for directional control. Table I is an example of survey data recorded at approximately every 45 meters.

Table I - Sample Survey Data Sheet.

Survey No.	Depth	Inc	Az	TVD	N/S	E/W	V/S
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	1993.00	0.90	132.29	1992.92	-10.52	11.56	8.45
3	2041.00	0.81	130.13	2040.91	-10.99	12.10	8.84
4	2086.00	0.81	136.13	2085.91	-11.42	12.56	9.18
5	2131.00	0.56	137.47	2130.91	-11.81	12.93	9.43
6	2175.00	1.00	132.19	2174.90	-12.23	13.36	9.74
7	2220.00	1.14	133.41	2219.89	-12.80	13.97	10.19
8	2264.00	1.17	130.37	2263.88	-13.39	14.64	10.67
9	2309.00	1.08	129.98	2308.88	-13.96	15.31	11.18
10	2353.00	0.89	138.15	2352.87	-14.48	15.85	11.57
11	2398.00	1.11	130.53	2397.86	-15.02	16.42	11.97
12	2442.00	1.30	129.65	2441.85	-15.62	17.13	12.50

The model studied in this study calculates the torque and drag in one-meter intervals. Therefore, the model uses linear interpolation for the areas in between the survey stations.

For example; if the survey stations are on 1830 meter and 1860 meter, and the inclination measured at these points are 70° and 75°, the model will use the linear interpolation to calculate the inclination at 1850 meter.

By linear interpolation an unknown value, y, can be find by two known coordinates (x_0, y_0) and (x_1, y_1):

$$y = y_0 + (y_1 - y_0)\frac{x-x_0}{x_1-x_0} \text{ ....(11)}$$

Hence, the value of inclination at 1850 meter can be calculated as:

$$y = 70 + (75 - 70)\frac{1850 - 1830}{1860 - 1830}$$

$$y = 73.3°$$

Same procedure can be followed for the calculation of azimuth values.

The calculation of inclination and azimuth in between survey stations by linear interpolation is an approach with an assumption that the inclination and azimuth changes linearly in between two stations that may not be the case in reality. Since it is practically impossible to take surveys every one meters, considering that a complete survey takes three to five minutes, linear interpolation approach is an easy and logical approach.

5.8 Normal Force Calculation

After calculating the interpolated values of inclination and azimuth and the buoyed weight of the unit drill string element, normal force can be calculated:

$$F_n = \sqrt{(F_t \Delta\phi sin\theta)^2 + (F_t \Delta\phi W sin\theta)^2} \quad \text{..(1)}$$

where,

F_t	is the tension force at the lower end of the string element.
$\Delta\phi$	is the change in azimuth angle over the string element.
θ	is the inclination at the lower end of the string element.
W	is the buoyed weight of the string element.

5.9 Friction Coefficient

Friction coefficient is a manual selection in the model. However, it has to be chosen reasonably to account for realistic values. Using the data from offset wells would be a logical approach. For standard drilling operations, the coefficient of friction with water-based mud would be around 0.25 for cased section. For open hole section it would be around 0.35. The coefficient of friction is dependent upon the condition of the well, the formation, mud selection, penetration rate.

In this study, friction coefficients (μ) of 0.25, 0.30 and 0.35 are used for cased and open hole sections, Appendix-C.

5.10 Calculation of Drag

Drag is calculated after the selection of the coefficient of friction.

$$F_t = W cos\theta \pm \mu F_n \qquad \text{.........................(2)}$$

where,

F_t is the increment in tension across the string element.
μ is the coefficient of friction between the string and wellbore/casing.

The value of drag is dependent upon the pipe motion, i.e. upwards or downwards. In the above formula, "±" sign accounts for this. The product of normal force and coefficient of friction is added to the component of section drill string weight while the motion is upwards and vice versa.

The calculation of drag starts from the bottom of the drill string and calculated at one-meter intervals. Each calculation are performed and added from bottom to top of the drill string up to the surface.

5.11 Calculation of Torque

Section torque is calculated after normal force calculation and determination of friction coefficient:

$$\Delta M = \mu F_n R \quad (3)$$

where,

ΔM is the increment in torque across the string element.
R is the radius of the string element.

The calculation of torque starts from the bottom of the drill string and calculated at one-meter intervals. Each calculation are performed and added from bottom to top of the drill string up to the surface.

5.12 Rotational Torque

The torque calculated with the model constructed is the frictional torque. The torque generated by drill string rotation has to be estimated for cumulative torque calculation. Rotational torque depends on parameters like RPM and WOB and an observation is possible rather than a calculation by changing the drilling parameters. It is possible to observe the cumulative torque on the rotary table during drilling. Once the frictional torque is calculated, rotational torque can be back calculated by subtracting frictional torque from cumulative torque.

In this study, an estimation of rotational toque ranging from 2.0 klbf.ft to 4.0 klbf.ft is accounted for calculating the cumulative torque for different cases of the dataset available.

CHAPTER 6

RESULTS AND DISCUSSION

In order to validate the developed torque and drag model, five case study drilling operations data are examined, namely Wells A, B, C, D and E. The wells are located in the Middle East Geomarket. Appendix-D gives the inclination and azimuth values of the wells data of which is used in this study.

6.1 Data Charts

Charts for torque calculation at various depths along the directionally drilled 6" hole section intervals are presented in this section. The introduced methodology performs the torque and drag calculation based on the actual wellbore geometry, input data and BHA configuration in use. It is observed that the torque and drag calculations are easily conducted by means of the proposed computer program instantly whenever deemed necessary. Appendix-E and Appendix-F respectively give the code flow and computer program used in this study.

It is important to ensure that the torque and weight indicator gauges of the rig are as accurate as possible. In addition, the comparison of different wells' data shall be compared after ensuring that the tools of measurements are as accurate as possible, and performed the measurements using the same calibration mechanisms. The accuracy and calibration of the rig instruments enable the comparison of the data collected from different wells.

6.1.1 Application on Well-A Case Study

Figure XVI gives the BHA details of Well-A. It is observed that the bit depth is input to be at 3011 m MD. The BHA item definition for each and every member of the BHA is summarized in this Userform. The OD, ID and Unit Weight for each item string is calculated based on the OD and ID input, and finally the defined length for each string item is calculated based on the information input by the user.

Well: Well-A

Bit Depth, m: 3011

BHA Item	OD, in	ID, in	U.Wt, lbs/ft	Length, m
5" 19.50 D	5	4.276	17.864091	1232.25
Crossover	5.5	3	56.525	0.83
3-1/2" 13.3	3.5	2.764	12.263408	1274.56
3 1/2" HW	3.5	2.063	21.264122	170.81
3-1/2" 13.3	3.5	2.764	12.263408	231.73
3 1/2" HW	3.5	2.063	21.264122	28.62
Jar	4.83	2.25	48.588624	8.77
3 1/2" HW	3.5	2.063	21.264122	28.53
ADN-4	4.75	2.25	46.55	7.21
SonicScope	5.875	3.16	65.249866	9.54
IMPulse 20	5.25	2.25	59.85	10.26
PD 475 Rec	5.25	2	62.67625	2.23
Flex Collar	4.75	2	49.37625	1.43
PD 475 X5	5.875	3.64	56.567626	4.06
6" Bit PDC	6	1.25	91.60375	0.17

Figure XVI - Well-A 6" BHA Details.

Figure XVII gives the torque chart for Well-A for various depth points. The torque for the given wellbore geometry and BHA in hole at selected depth points is calculated for two different OH (Open Hole) friction factors, for 0.25 and 0.30 respectively. The advantage of the introduced methodology is the ability to input the FF as necessary and observe which FF magnitude most efficiently calculated the torque value in comparison to the actual torque observation. An average rotational torque of 2.0 klbf.ft is included in the torque calculations.

Additionally, the actual rotational torque is back calculated by subtracting the model calculated frictional torque in each depth point (FF= 0.25) from the actual drilling torque. Hence, torque values are adjusted and demonstrated, which can actually be performed following drilling for accurate determination of rotational torque.

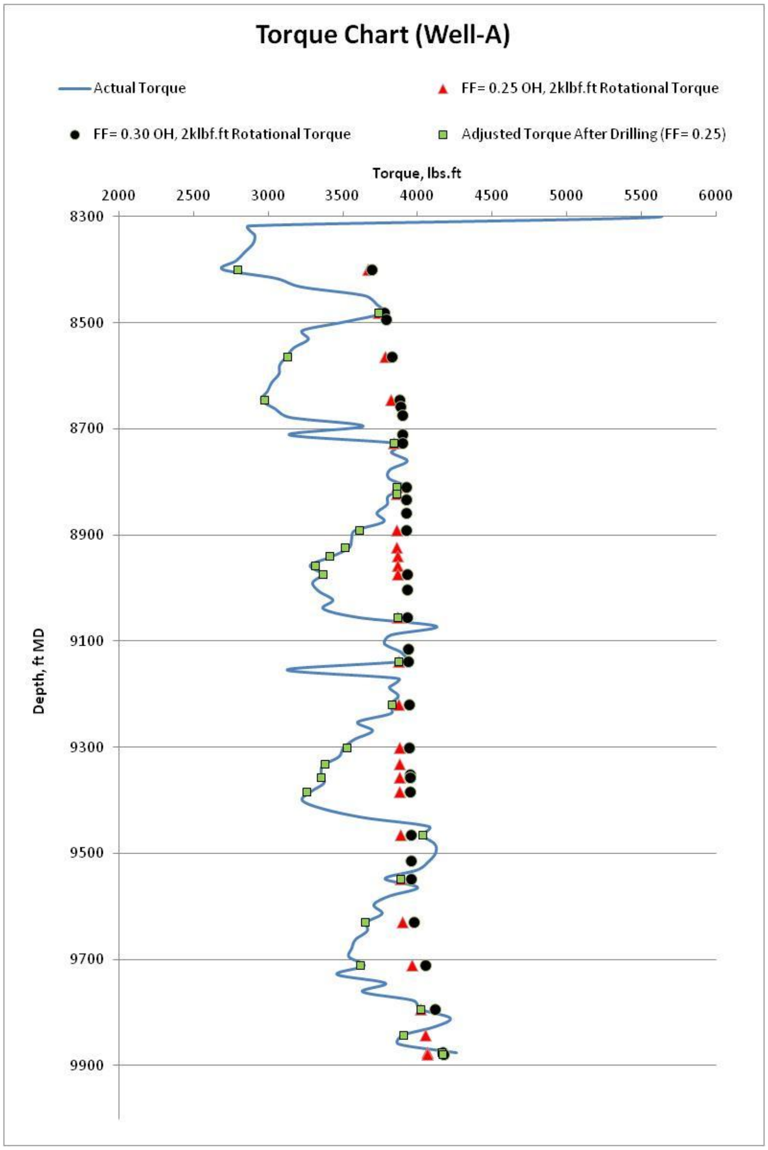


Figure XVII - Torque Chart Well-A.

Figure XVIII gives the histogram of Well-A for the comparison of the actual and calculated torque values when the input friction factor (FF) for the OH section of the well is taken to be 0.25. The histogram reveals that the majority of the error percentages (error between the actual and calculated torque) is less than 10%.

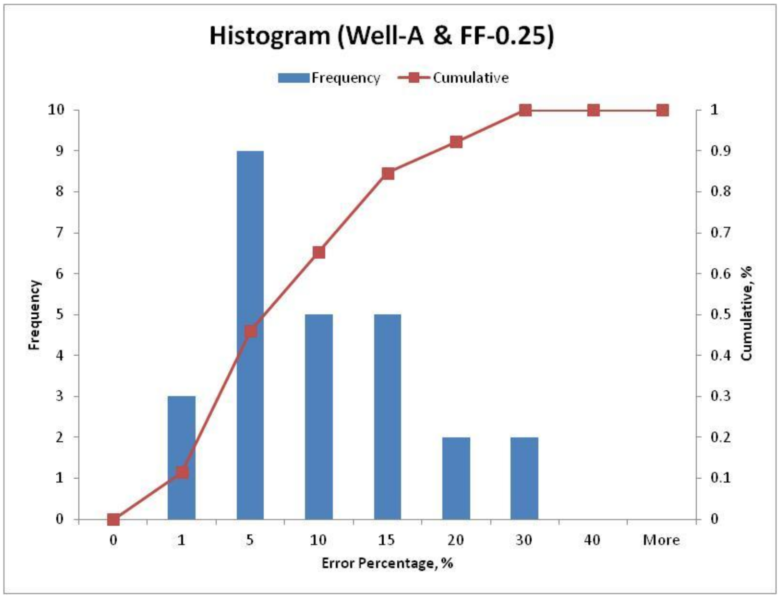


Figure XVIII - Well-A OH FF-0.25 Histogram for Torque Data.

Figure XIX likewise gives the histogram for Well-A torque error distribution for the 0.30 OH FF. Similar to that of 0.25 FF the majority of the error percentages are less than 10%.

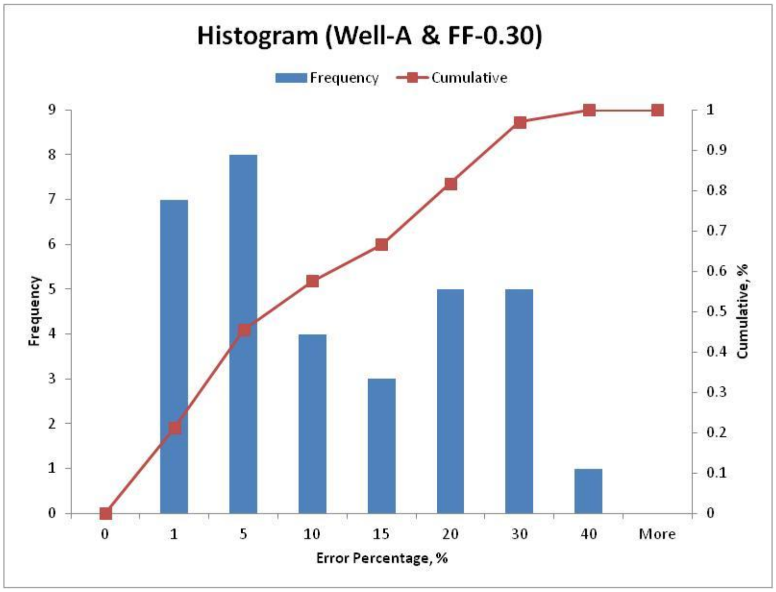


Figure XIX - Well-A OH FF-0.30 Histogram for Torque Data.

Figure XX gives the theoretically calculated drag data for the Well-A at the section TD (Total Depth). Azimuth correction is applied in the calculations for this study when the drag charts are plotted. The drag calculations are very important to be monitored, especially in high angle wells, because excessive cuttings loading in the annulus may result in high overpulls, and consequent stuck pipe events if not handled accordingly. Also while drilling; the drag forces are important to be monitored because the more the wall contact area and the more the drag. The driller is going to need to slack off more axial load in order to ensure the same weight on bit is transferred with increased wall contract area. The incremental slack off string weight may result in undesired buckling incidents. In the scope of this study, the actual hook load data is not available. For this reason, the axial theoretical loads are available only.

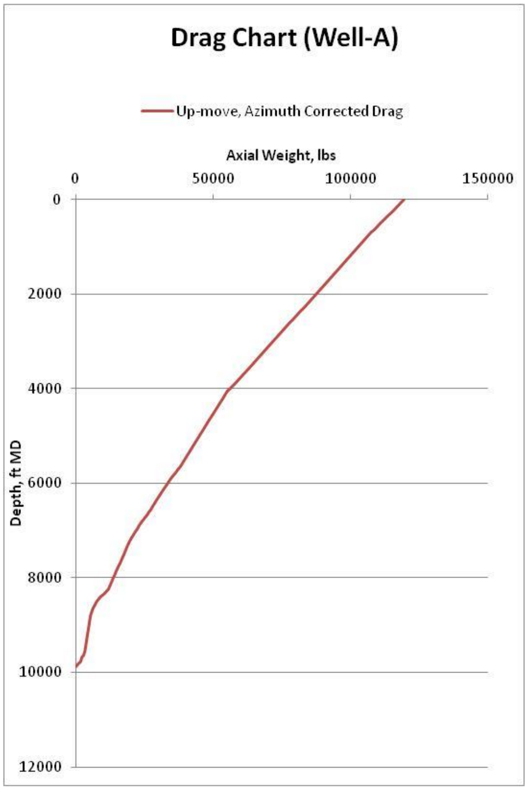
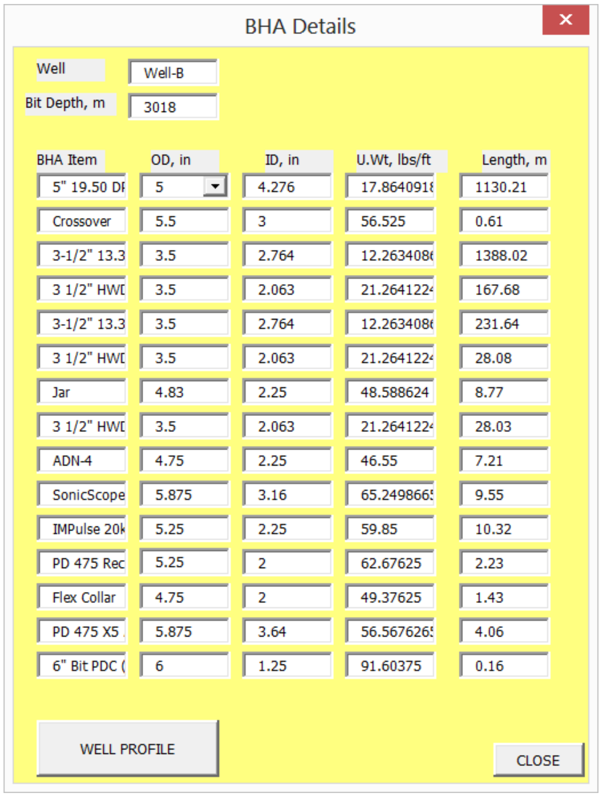


Figure XX - Drag Chart Well-A.

6.1.2 Application on Well-B Case Study

Figure XXI gives the BHA details of the Well-B. The string is composed of a rotary steerable BHA with 3 1/2" and 5" DP strings.



Well: Well-B

Bit Depth, m: 3018

BHA Item	OD, in	ID, in	U.Wt, lbs/ft	Length, m
5" 19.50 D	5	4.276	17.864091	1130.21
Crossover	5.5	3	56.525	0.61
3-1/2" 13.3	3.5	2.764	12.263408	1388.02
3 1/2" HW	3.5	2.063	21.264122	167.68
3-1/2" 13.3	3.5	2.764	12.263408	231.64
3 1/2" HW	3.5	2.063	21.264122	28.08
Jar	4.83	2.25	48.588624	8.77
3 1/2" HW	3.5	2.063	21.264122	28.03
ADN-4	4.75	2.25	46.55	7.21
SonicScope	5.875	3.16	65.249866	9.55
IMPulse 20	5.25	2.25	59.85	10.32
PD 475 Re	5.25	2	62.67625	2.23
Flex Collar	4.75	2	49.37625	1.43
PD 475 X5	5.875	3.64	56.567626	4.06
6" Bit PDC (	6	1.25	91.60375	0.16

Figure XXI - Well-B 6" BHA Details.

Figure XXII gives the Well-B torque chart. The estimated torque magnitudes are presented for three (3) different FFs, with an average of 2.5 klbf.ft rotational torque value. Obviously, the 0.35 FF magnitude applied revealed the greatest torque estimates.

Additionally, the actual rotational torque is back calculated by subtracting the model calculated frictional torque in each depth point (FF= 0.25) from the actual drilling torque. Hence, torque values are adjusted and demonstrated, which can actually be performed following drilling for accurate determination of rotational torque.

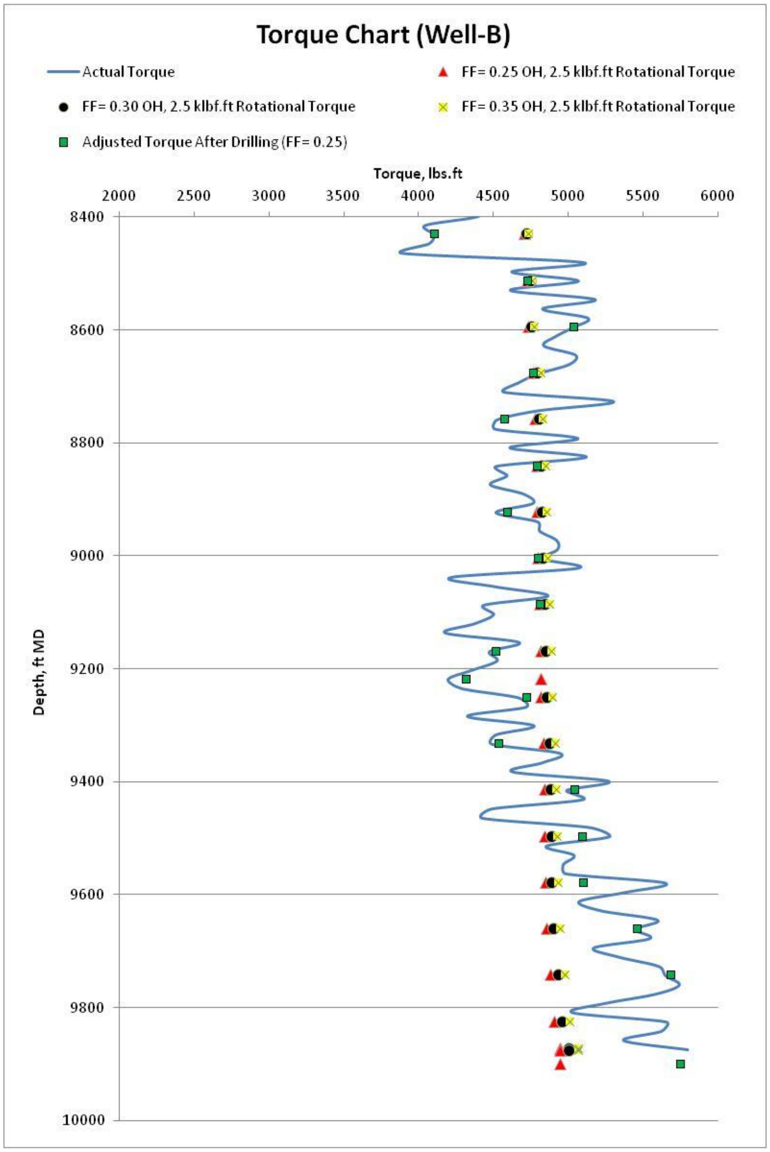


Figure XXII - Torque Chart Well-B.

Figure XXIII gives the histogram of Well-B error percentage distribution when the FF is taken at 0.25 in the open hole interval. The data indicate that 60% of the error percentage data are less than 15%.

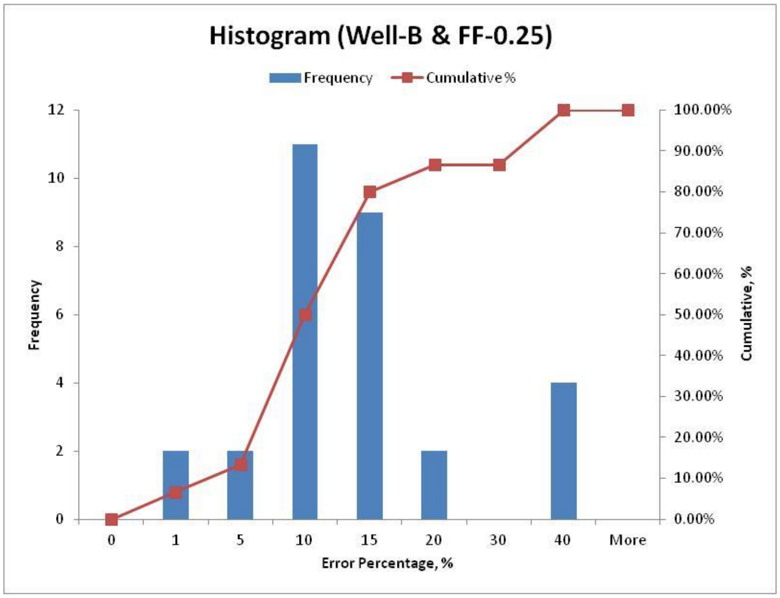


Figure XXIII - Well-B OH FF-0.25 Histogram for Torque Data.

Figure XXIV gives the histogram of Well-B error percentage distribution when the FF is taken at 0.30 in the open hole interval.

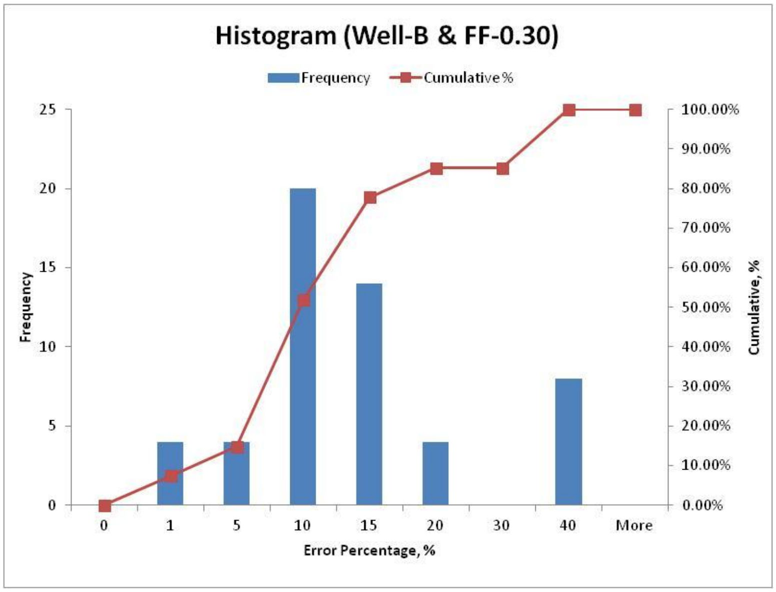


Figure XXIV - Well-B OH FF-0.30 Histogram for Torque Data.

Figure XXV gives the histogram of Well-B error percentage distribution when the FF is taken at 0.35 in the open hole interval.

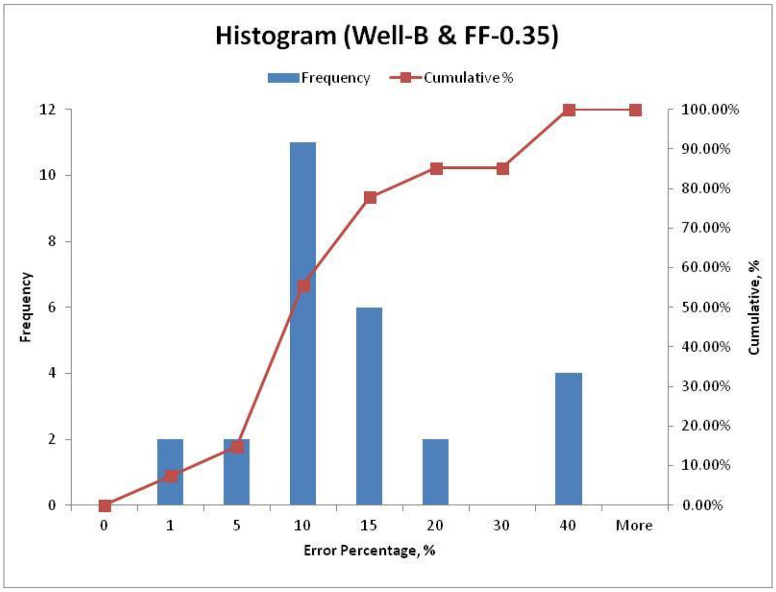


Figure XXV - Well-B OH FF-0.35 Histogram for Torque Data.

Figure XVI gives the theoretically calculated drag data for the Well-B at the section TD. It is easily observed that the drag chart follows the wellbore's directional trajectory.

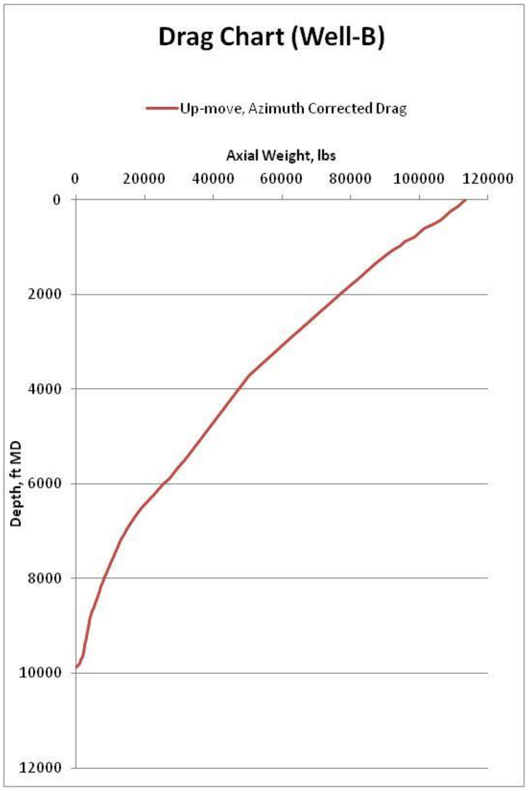
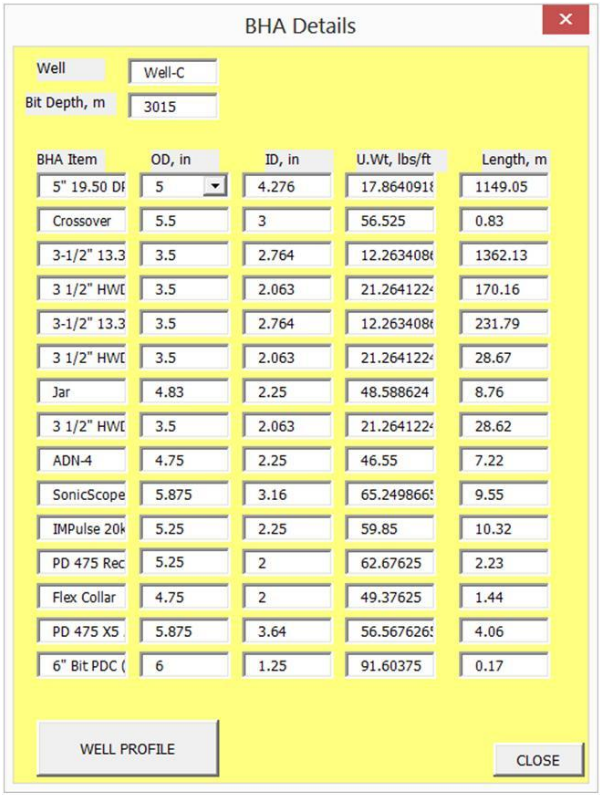


Figure XXVI - Drag Chart Well-B.

6.1.3 Application on Well-C Case Study

Figure XXVII gives the details of the Well-C's BHA items. The bit in the hole is a 6" PDC bit.



Well: Well-C
Bit Depth, m: 3015

BHA Item	OD, in	ID, in	U.Wt, lbs/ft	Length, m
5" 19.50 D	5	4.276	17.864091	1149.05
Crossover	5.5	3	56.525	0.83
3-1/2" 13.3	3.5	2.764	12.263408	1362.13
3 1/2" HWD	3.5	2.063	21.264122	170.16
3-1/2" 13.3	3.5	2.764	12.263408	231.79
3 1/2" HWD	3.5	2.063	21.264122	28.67
Jar	4.83	2.25	48.588624	8.76
3 1/2" HWD	3.5	2.063	21.264122	28.62
ADN-4	4.75	2.25	46.55	7.22
SonicScope	5.875	3.16	65.249866	9.55
IMPulse 20k	5.25	2.25	59.85	10.32
PD 475 Rec	5.25	2	62.67625	2.23
Flex Collar	4.75	2	49.37625	1.44
PD 475 X5	5.875	3.64	56.567626	4.06
6" Bit PDC (	6	1.25	91.60375	0.17

Figure XXVII - Well-C 6 " BHA Details.

Figure XXVIII gives the torque chart for Well-C. Two different FF for the OH section is used for the torque calculations. The calculations indicate that there is no significant difference between the calculated torque values when different FF values are used. The average rotational torque is taken as 4.0 klbf.ft in the calculations.

Additionally, the actual rotational torque is back calculated by subtracting the model calculated frictional torque in each depth point (FF= 0.25) from the actual drilling torque. Hence, torque values are adjusted and demonstrated, which can actually be performed following drilling for accurate determination of rotational torque.

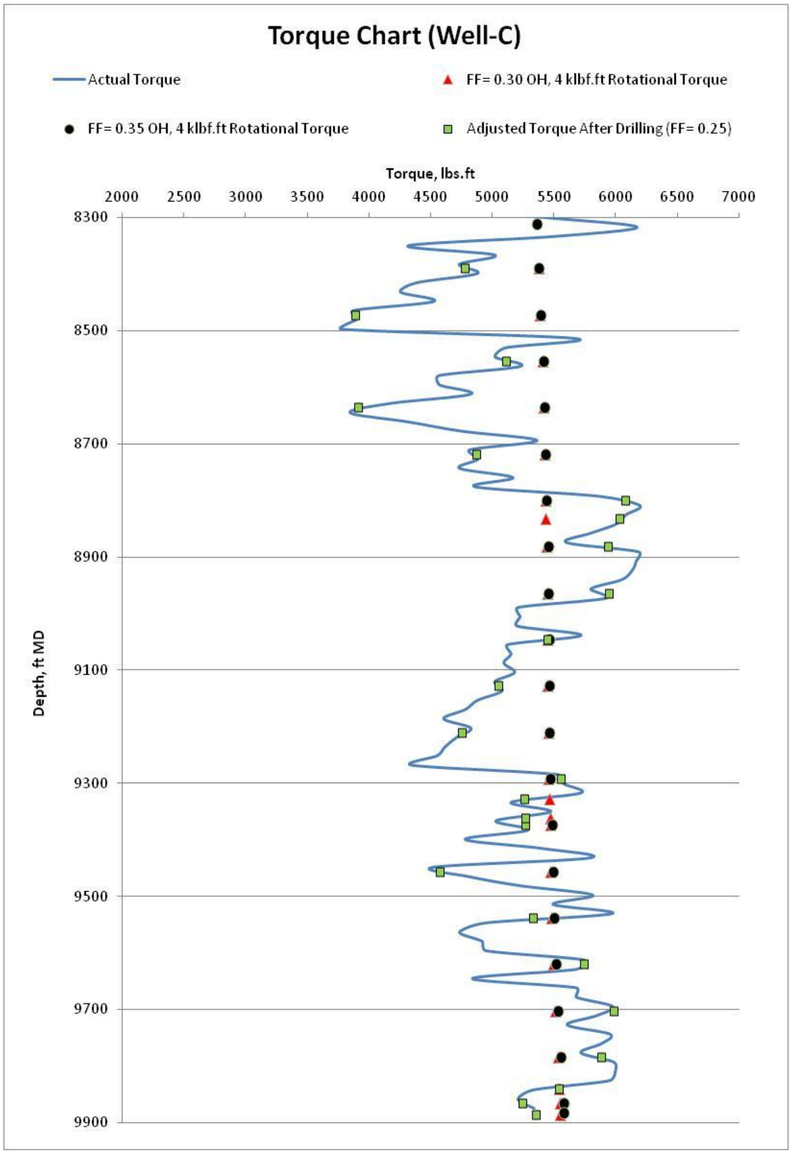


Figure XXVIII - Torque Chart Well-C.

Figure XXIX gives the error percentage histogram for Well-C with 0.30 FF in the OH.

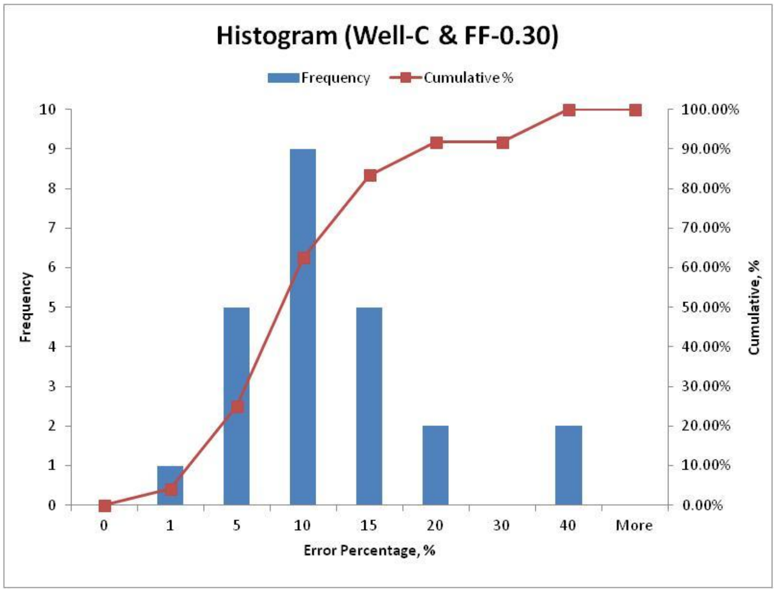


Figure XXIX - Well-C OH FF-0.30 Histogram for Torque Data.

Figure XXX gives the error percentage histogram for Well-C with 0.35 FF in the OH. The result indicates that a better torque estimation is achieved when the FF in OH is taken at 0.35.

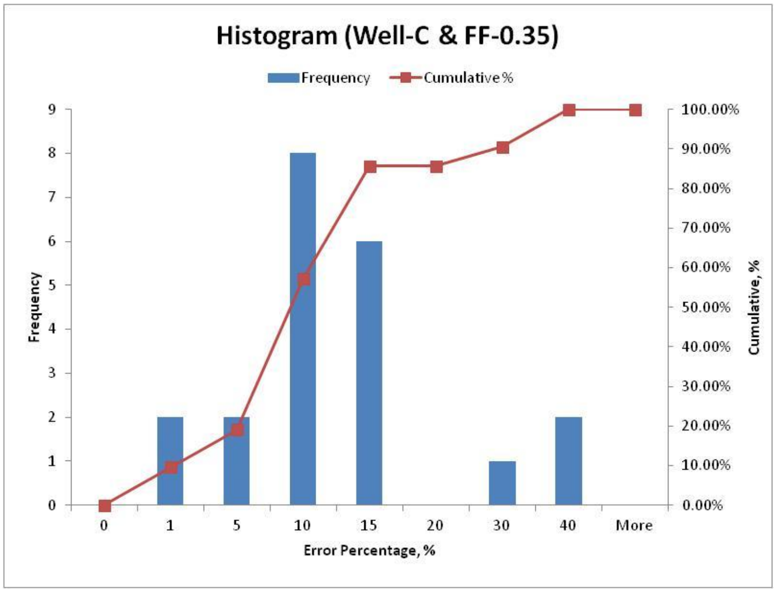


Figure XXX - Well-C OH FF-0.35 Histogram for Torque Data.

Figure XXXI gives the theoretically calculated drag data for the Well-C at the section TD.

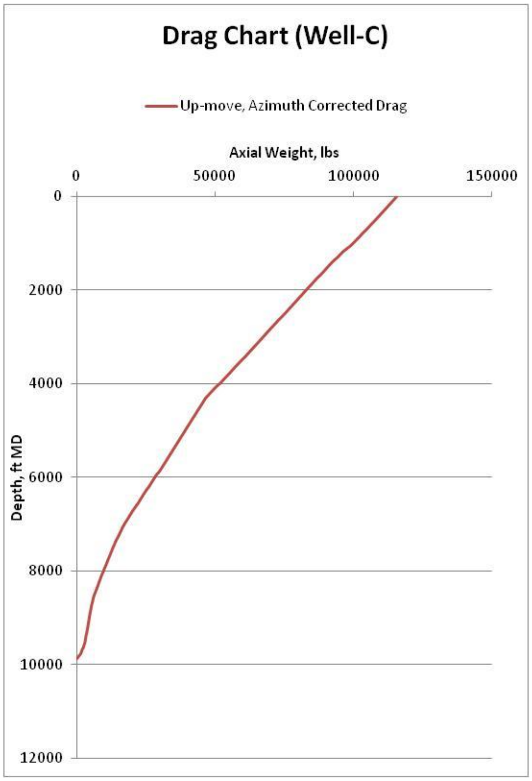


Figure XXXI - Drag Chart Well-C.

6.1.4 Application on Well-D Case Study

Figure XXXII gives the details of the Well-D's BHA items. The bit depth in the program is entered at 3095 m MD.

Well: Well-D

Bit Depth, m: 3095

BHA Item	OD, in	ID, in	U.Wt, lbs/ft	Length, m
5" 19.50 D	5	4.276	17.864091	1150.228
Crossover	5.5	3	56.525	0.61
3-1/2" 13.3	3.5	2.764	12.263408	1445.59
3 1/2" HW	3.5	2.063	21.264122	167.78
3-1/2" 13.3	3.5	2.764	12.263408	231.27
3 1/2" HW	3.5	2.063	21.264122	27.55
Jar	4.83	2.25	48.588624	8.65
3 1/2" HW	3.5	2.063	21.264122	28.362
ADN-4	4.75	2.25	46.55	7.21
SonicScope	5.875	3.16	65.249866	9.55
IMPulse 20	5.25	2.25	59.85	10.32
PD 475 Rec	5.25	2	62.67625	2.23
Flex Collar	4.75	2	49.37625	1.43
PD 475 X5	5.875	3.64	56.567626	4.06
6" Bit PDC (	6	1.25	91.60375	0.16

Figure XXXII - Well-D 6" BHA Details.

Figure XXXIII gives the torque chart for Well-D. Two different FF for the OH section is used for the torque calculations. The average rotational torque is taken to be 3.0 klbf.ft in the calculations.

Additionally, the actual rotational torque is back calculated by subtracting the model calculated frictional torque in each depth point (FF= 0.25) from the actual drilling torque. Hence, torque values are adjusted and demonstrated, which can actually be performed following drilling for accurate determination of rotational torque.

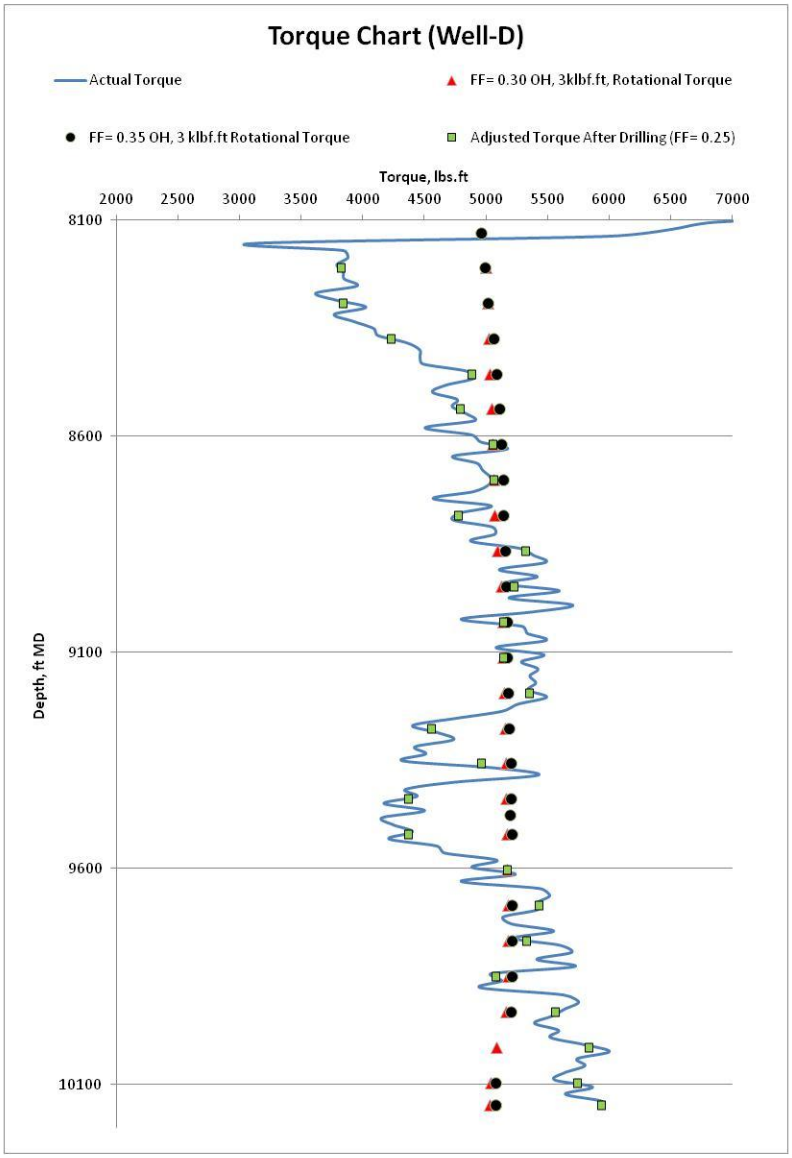


Figure XXXIII - Torque Chart Well-D.

Figure XXXIV gives the error percentage histogram for Well-D with 0.30 FF in the OH.

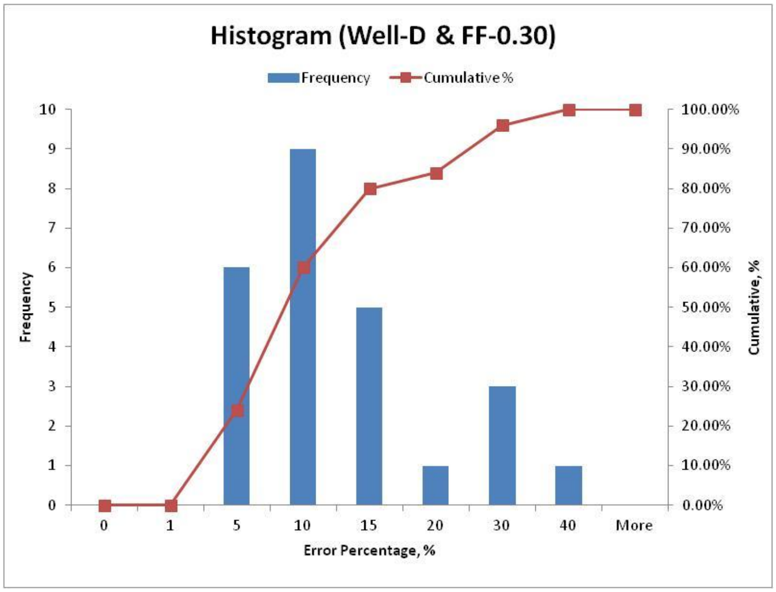


Figure XXXIV - Well-D OH FF-0.30 Histogram for Torque Data.

Figure XXXV gives the error percentage histogram for Well-D with 0.35 FF in the OH.

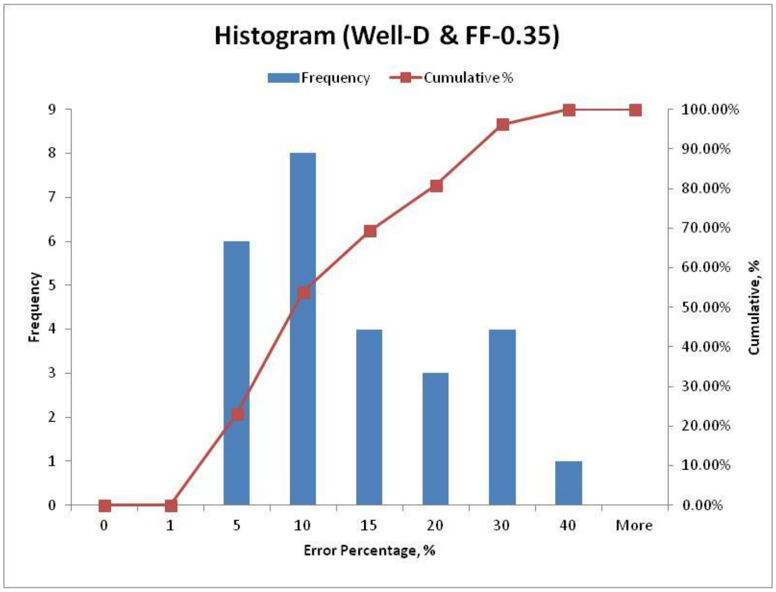


Figure XXXV - Well-D OH FF-0.35 Histogram for Torque Data.

Figure XXXVI gives the theoretically calculated drag data for the Well-D at the section TD.

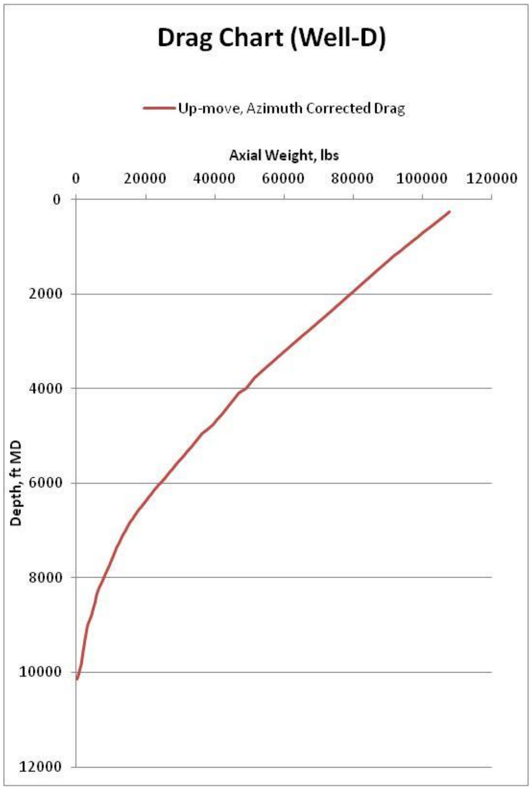


Figure XXXVI - Drag Chart Well-D.

6.1.5 Application on Well-E Case Study

The planning of the directional trajectory of Well-E was performed considering the Torque and Drag Analysis of the previous high angle wells drilled in the field, because the 6" hole section of the Well-E was drilled approximately for an interval of 900 m. Figure XXXVII gives the details of the Well-E's BHA items. The bit depth in the program is entered at 3380 m MD.


BHA Details

Well: Well-E
Bit Depth, m: 3380

BHA Item	OD, in	ID, in	U.Wt, lbs/ft	Length, m
5" 19.50 D	5	4.276	17.864091	1201.73
Crossover	5.5	3	56.525	0.6
3-1/2" 13.3	3.5	2.764	12.263408	1100
3 1/2" HW	3.5	2.063	21.264122	169.86
3-1/2" 13.3	3.5	2.764	12.263408	608.41
3 1/2" HW	3.5	2.063	21.264122	28.67
Jar	4.83	2.25	48.588624	8.76
3 1/2" HW	3.5	2.063	21.264122	28.62
3-1/2" 13.3	3.5	2.764	12.263408	173.93
3 1/2" HW	3.5	2.063	21.264122	28.62
ADN-4	4.75	2.25	46.55	7.22
SonicScope	5.875	3.16	65.249866	9.6
IMPulse 20	5.25	2.25	59.85	10.32
PD 475 Rec	5.25	2	62.67625	2.23
Flex Collar	4.75	2	49.37625	1.43

Figure XXXVII - Well-E 6" BHA Details.

Figure XXXVIII gives the torque chart for Well-E. The FF for the OH section used for the torque calculations is 0.30. The average rotational torque is taken to be 3.5 klbf.ft in the calculations.

Additionally, the actual rotational torque is back calculated by subtracting the model calculated frictional torque in each depth point (FF= 0.25) from the actual drilling torque. Hence, torque values are adjusted and demonstrated, which can actually be performed following drilling for accurate determination of rotational torque.

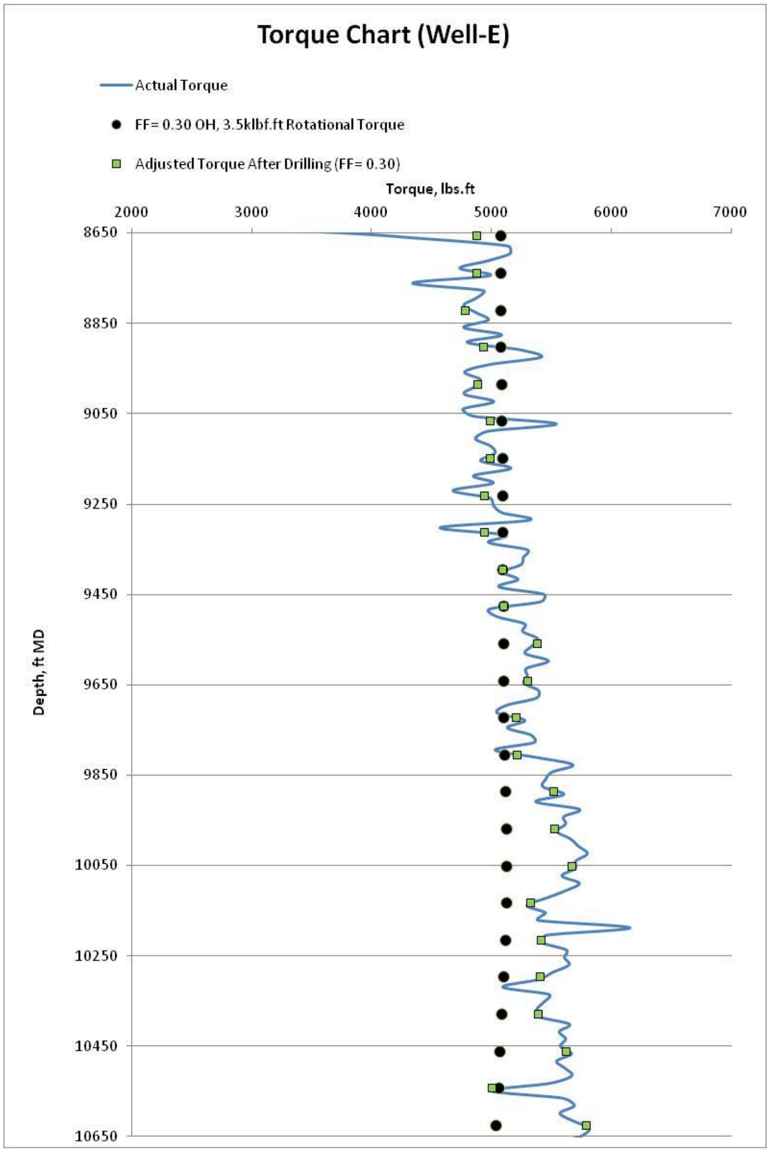


Figure XXXVIII - Torque Chart Well-E.

Figure XXXIX gives the error percentage histogram for Well-E with 0.30 FF in the OH.

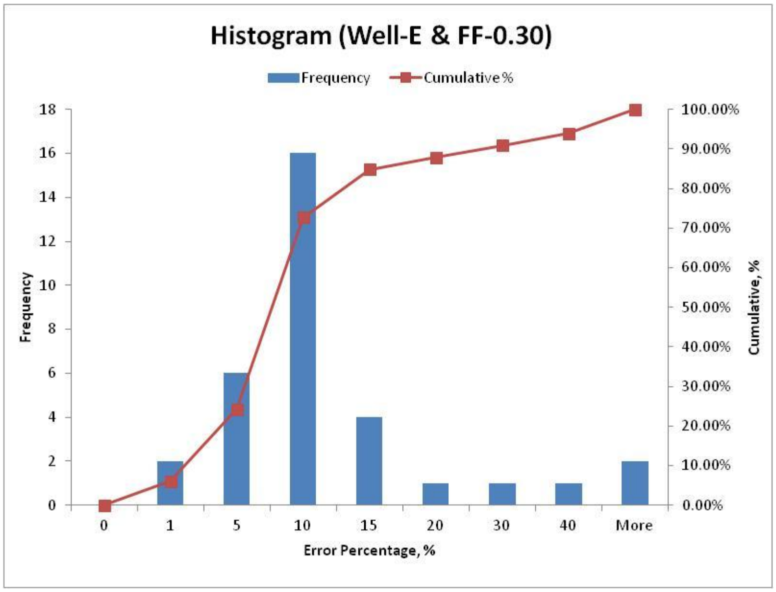


Figure XXXIX - Well-E OH FF-0.30 Histogram for Torque Data.

Figure XL gives the theoretically calculated drag data for the Well-E at section TD.

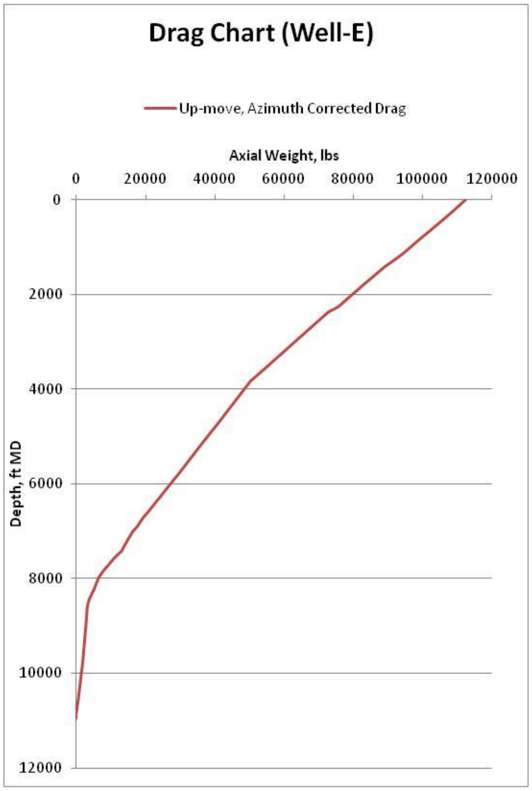


Figure XL - Drag Chart Well-E.

6.1.6 Histogram of All Data Points

Figure XLI gives the histogram of all 341 data points acquired in this study. It is observed that approximately 85% of the errors (difference between the theoretical and actual torque) are equal or less than 20%.

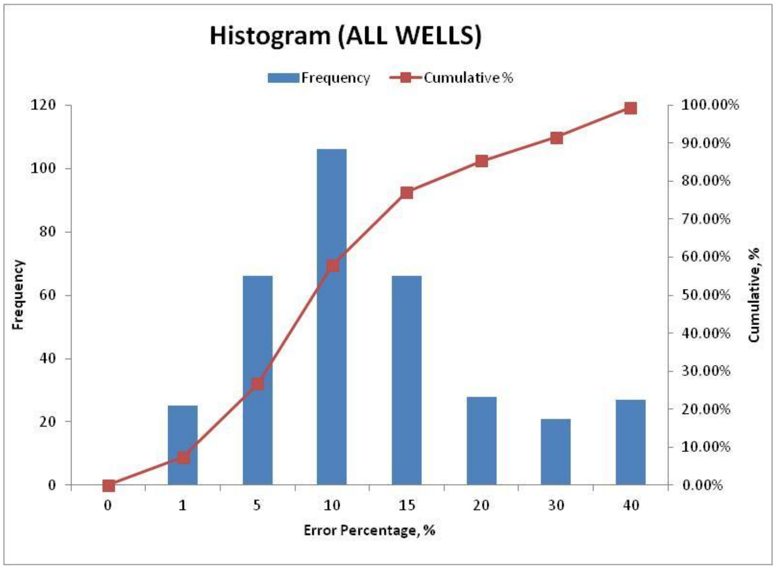


Figure XLI - Histogram of All Error Points.

6.2 Tortuosity Effects

The planning of the highly deviated and horizontal wells does not take into consideration to a full extend the hole spiraling or oscillations within the wellbore, which should be considered for the tortuosity to occur along the wellbore trajectory. The actual well path can tremendously be affected with the difference in between the actual and the planned torque and drag calculations since well trajectory can be under a major impact due to the unforeseen torque and losses for drag. In this study the torque and drag calculation stations are taken for each and every 1 m interval. This way all of the tortuosity effects are going to be minimized when calculating the actual torque and drag trends.

6.3 Application of Model at the Oilfield

The torque and drag monitoring methodology being recommended in the scope of this study can give significant results to the rig site personnel, without being in need of using commercial computer programs. Sometimes the cost of commercial computer program packages can be very costly to be afforded by mid-sized companies. The data to be used by means of utilizing the methodology of this study is going to define the reach capability for the drilling and casing/liner strings. The output data is critical in determining whether the actual wellbore trajectory is following the planned data input (i.e. friction factor). Deep analysis for torque and drag especially by the rig site personnel is important because in case of observing a friction factor greater than the expected, the rig crew can take the necessary actions and prevent the occurrence of undesired events. For example, if the wellbore needs the addition of more lubricant prior the commencement of the liner set, the rig site staff may choose to ensure the optimum lubricant is added to the drilling fluid in a timely manner.

In case the rig site staff is equipped with the correct training and in a position to suggest the optimization of the wellbore trajectory for more efficient drilling, a recommendation by the rig site can be put forward. Following the determination of accurate friction factors, a suggestion to the office based engineering team can be initiated by the rig site staff in time. Since in most applications the office based team is not working on a 24 hours basis, and in some circumstances significant interval lengths could be drilled during 12-hour shifts.

Another advantage of the proposed methodology is the ability to estimate the torque and drag behavior at the depths input into the program. Also in the planning stage the surface torque for the BHA planned to be used can be estimated for the complete interval. Any significant deviation from the estimated torque and drag analysis is going to indicate that the torque trend is deviating from that is planned and a problem may be escalating downhole, which shall be addressed at the earliest possibility.

The outcome of the histograms indicate that the Torque magnitudes based on the wellbore geometry and BHA configuration is easily calculated by means of using the computer program prepared for the scope of this study with reasonably small error ranges.

While drilling the torque values are desired to be as low as practically possible. However, actual rotational torque to be encountered in the wellbore is not easy to be calculated accurately. The assumption of the proposed model is that the loads on the drill string result only from the effects of gravity and friction that occurs due to contact between the drill string and wellbore [26] and the torque chart calculations are performed considering different rotational torque values at the bit ranging in between 2.0 to 4.0 klbf.ft.

CHAPTER 7

CONCLUSIONS

A quick calculation model, based on Soft String Torque and Drag Theory [23] is constructed for oilfield calculations during drilling operations. For the construction of the model, many parameters are considered and calculated such as; BHA definition, well profile (inclination and azimuth), drilling fluid density, buoyed weight, outer and inner diameters of drill string components, string weight, friction factors and normal and axial forces acting on the drill string. The model constructed calculates the frictional torque and drag values at every one meters unit element and assumes the values are the same throughout the defined unit segment. The model is also capable to calculate the estimated surface torque for the BHA planned to be used for the complete interval.

The model is applied on five case study drilling operations namely the drilling of Well-A, Well-B, Well-C, Well-D and Well-E. The results were evaluated based on the histograms and actual data and small error margins prove that the model constructed would be of great benefit to oilfield personnel to make torque and drag interpretations.

For each well different friction factors are used for the 6" OH intervals together with other solid results exercised as explained. The calculated frictional torque magnitudes are increased with the drilling torque while drilling (unknown, but input as per industry practice) to calculate the surface rotational torque at each depth point identified. The on bottom drilling torque is a parameter that cannot be calculated. The on bottom drilling torque is a function of various drilling parameters such as WOB, RPM, Flow Rate, Bit Type and hole condition/geometry to list. Therefore the on bottom torque at the bit is selected in the scope of this study. Naturally the frictional torque magnitudes calculated are observed to be significantly different than the actual surface torque observations.

Whenever the frictional torque values were increased by the on bottom drilling torque, the surface torque estimations were observed to be very close to the actual surface torque magnitudes recorded, giving much lower error percentages.

The model constructed can be used by the oilfield personnel to:

- Calculate torque and drag expected magnitudes and construct trends not only for single depth points but also for complete interval.

- Determine whether the drilling operations are ongoing within the allowable torque and drag limits or not. Take precautions if excess torque and drag values are encountered.

- Question the drilling parameters or hole conditions in the case of excessive torque and drag values are occurring.

- Determine reasonable friction factor values taken for future nearby wells.

- Design the drilling operations to ensure that the torque and drag limitations of the BHA proposed are not going to be exceeded while drilling.

The risk of drilling directional and horizontal wells increases with complexity of the well profile. The torque and drag model constructed can be of great use to eliminate operational risks, NPTs, downhole tools losses, and consequently economical losses.

CHAPTER 8

RECOMMENDATIONS

The study can be further improved if the effects of hole size, clearance and post-buckling phenomena are deployed in the model in a practical manner as they will increase the complexity.

Use of friction factor database is also important for the accuracy of the model as there is a considerable amount of information available in the literature for different oilfields. Using reliable friction factors from offset wells would be a good practice.

Integration of a casing wear algorithm into the model would eliminate the errors and yield to calculations that are more accurate.

Accuracy of the model would increase if an algorithm is integrated to define drill string elements like stabilizers, heavy weight drill pipes, drill collars, conventional drill pipes etc. as maximum stresses of these are different.

The proposed model can be upgraded so that for each depth interval the actual on bottom torque is going to be determined, consequently which is going to be used for the calculation of the actual OH FF. The actual OH FF is going to be placed in the calculation flow and remain fixed in the rest of the torque and drag calculations for deeper intervals. This would improve the reliability of the model.

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APPENDIX A

DRILL STRING DESIGN FLOWCHART

Drill string design means determination of the drill string length, drill string weight and grades of drill pipes to be used for drilling operations. It depends on many parameters like hole profile, target depth, hole size, mud weight, safety factor, etc.

In order to make a proper drill string design, below flowchart can be used:

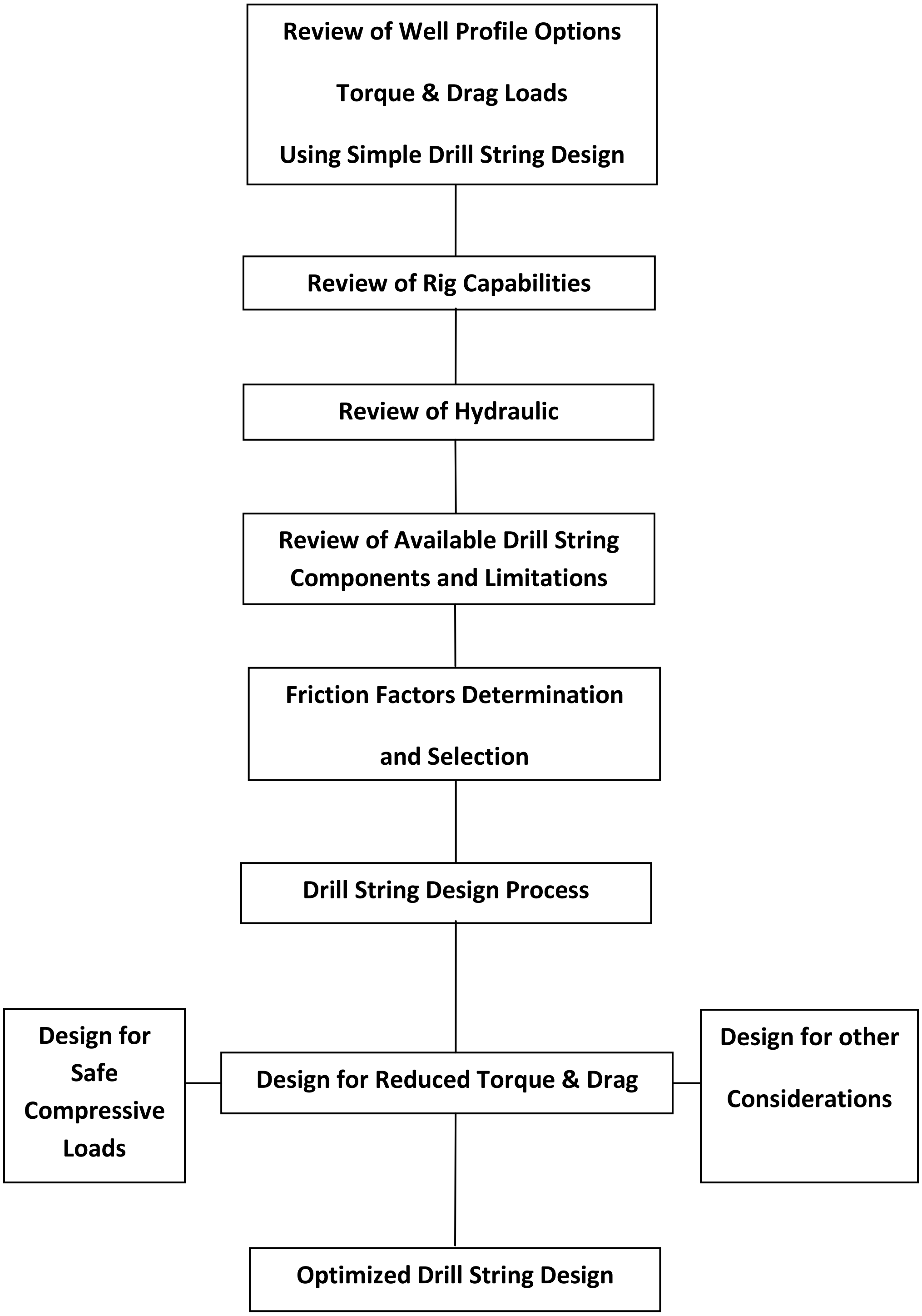


Figure XLII – Drill String Design Flowchart.

APPENDIX B

DRILL PIPE DATA TABLES

Drill string design is one of the most important part of well planning phase prior to drilling operations. Drill pipes are made of steel and they have limitations in terms of torsional yield strength and tensile yield strength. The size and grade of a drill pipe is the identifier of these limits.

Below table is an example of 5" drill pipe properties from NOV Grant Prideco Manual and available to be used as a drill pipe data reference [33]. NOV Grant Prideco is the world's largest supplier of drill pipe and drill stem accessories.

Table II: 5" Drill Pipe Properties.

OD Size,in	Nominal Weight, lb/ft	Grade and Upset Type	Torsional Yield Strength, ft-lb	Tensile Yield Strength,lb
5	19.5	X-95 IEU	52100	501100
5	19.5	G-105 IEU	57600	553800
5	19.5	S-135 IEU	74100	712700
5	19.5	Z-140 IEU	76800	738400
5	19.5	V-150 IEU	82300	791200
5	26.5	E-75 IEU	52300	530100
5	26.5	X-95 IEU	66200	671500
5	26.5	G-105 IEU	73200	742200
5	26.5	S-135 IEU	94100	954300
5	26.5	Z-140 IEU	97500	989600
5	26.5	V-150 IEU	104500	1060300

For the rest of the drill pipe sizes and grades the same manual can be used.

Once the torque and drag profile is created, the table can be used to determine whether the calculated values are within the operating limits of the drill string or not.

This approach will enable the engineer to make a quick interpretation about the drill string design. It also has to be taken into account that these specifications changes with time because of wear.

APPENDIX C

RECOMMENDED FRICTION FACTORS

Mason states [34] friction factor to be used in torque and drag calculations is a sophisticated area for engineers. Generally, each operation and each oilfield have their own set of friction factors that is determined from previous experience.

In order to determine the friction factor to be used, engineer would make a back-calculation from the operations in offset wells.

Nonetheless, Table III can be used as a starting point if there is no friction factor data available. These friction factors should be updated with new values found from back calculating.

Table III: Default Friction Factors Recommended.

	Water-Based Mud		Oil-Based Mud	
Operation	**Cased Hole**	**Open Hole**	**Cased Hole**	**Open Hole**
Drilling 12 1/4" Hole	0.25	0.30	0.20	0.20
Running 9 5/8" Casing	0.30	0.40	0.25	0.40
Drilling 8 1/2" Hole	0.25	0.30	0.20	0.20
Running 7" Liner	0.30	0.40	0.20	0.30
Running Completion Tubing	0.25			

APPENDIX D

WELL PROFILES

The planned vs. actual inclinations of the wells analyzed in the scope of this study are as given in below charts respectively in Figure XLIII and XLIV. The data are plot in every 328 ft intervals. The charts depict that the planned trajectories were realized while drilling the wells. Well-E is noted to have an extended trajectory in comparison to the others.

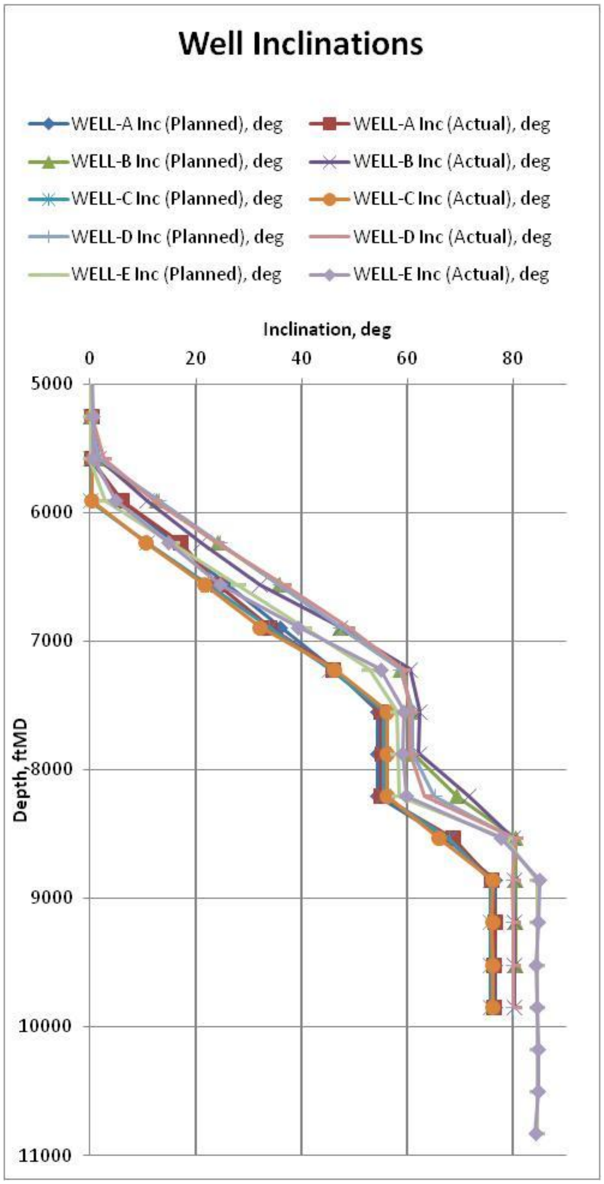


Figure XLIII - Well Inclinations.

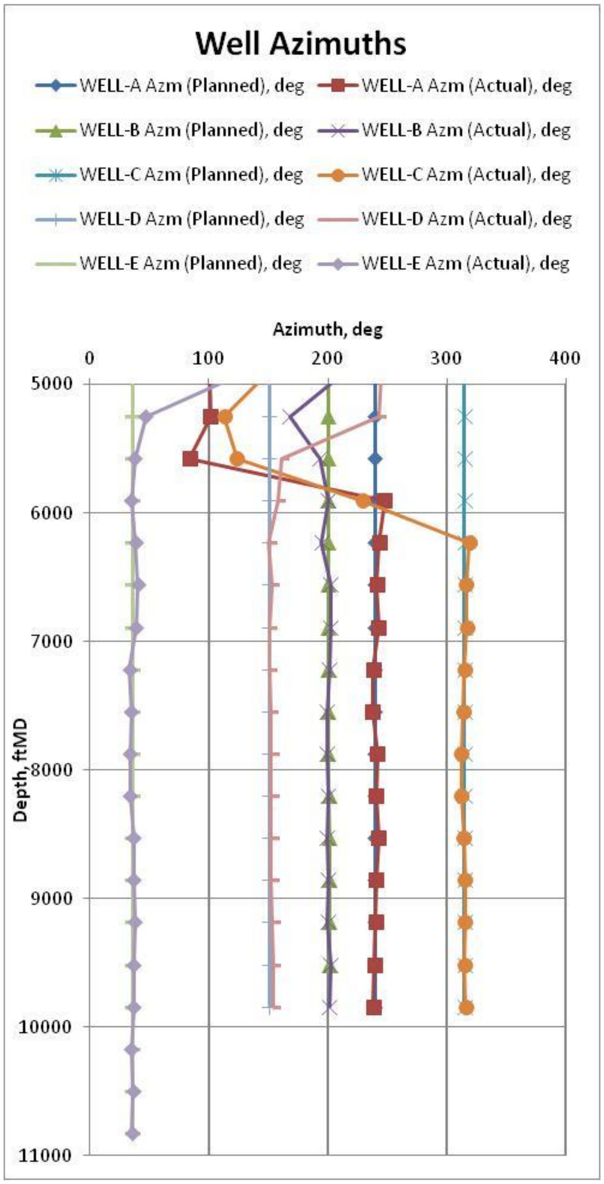


Figure XLIV - Well Azimuths.

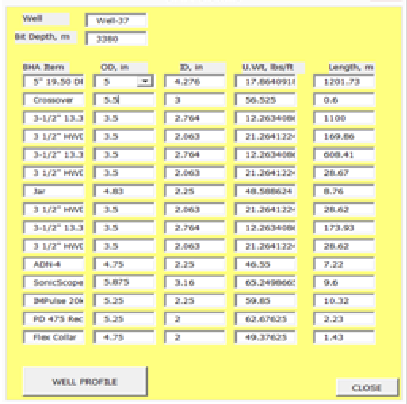
APPENDIX E

COMPUTER PROGRAM CODE FLOW

Visual Basic in Excel is used to make the calculations. Figure XLII gives the computer program code flow chart when using the excel computer program.

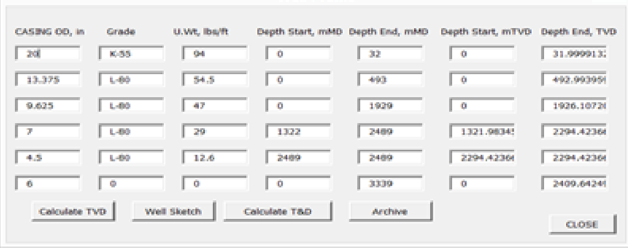
TORQUE AND DRAG RIG SITE MONITORING METHODOLOGY COMPUTER PROGRAM CODE FLOW

Input the BHA, survey, well profile details into the program



Well	Well-37
Bit Depth, m	3380

BHA Item	OD, in	ID, in	U.Wt, lbs/ft	Length, m
5" 19.50 DI	5	4.276	17.864091	1201.73
Crossover	5.5	3	56.525	0.6
3-1/2" 13.3	3.5	2.764	12.263408	1100
3 1/2" HWE	3.5	2.063	21.264122	169.86
3-1/2" 13.3	3.5	2.764	12.263408	608.41
3 1/2" HWE	3.5	2.063	21.264122	28.67
Jar	4.83	2.25	48.588624	8.76
3 1/2" HWE	3.5	2.063	21.264122	28.62
3-1/2" 13.3	3.5	2.764	12.263408	173.93
3 1/2" HWE	3.5	2.063	21.264122	28.62
ADN-4	4.75	2.25	46.55	7.22
SonicScope	5.875	3.16	65.249866	9.6
IMPulse 20	5.25	2.25	59.85	10.32
PD 475 Rec	5.25	2	62.67625	2.23
Flex Collar	4.75	2	49.37625	1.43



CASING OD, in	Grade	U.Wt, lbs/ft	Depth Start, mMD	Depth End, mMD	Depth Start, mTVD	Depth End, TVD
20	K-55	94	0	32	0	31.999913
13.375	L-80	54.5	0	493	0	492.99395
9.625	L-80	47	0	1929	0	1926.1072
7	L-80	29	1322	2489	1321.9834	2294.4236
4.5	L-80	12.6	2489	2489	2294.4236	2294.4236
6	0	0	0	3339	0	2409.6424

Run "MDtoTVDCalcs"

Run "Create_1m_WellSketchData"

Run "CalculateUnitWtList"

Run "UnitWeighteCalculator"

Run "ODCreator"

Run "TorqueDragCalculationWellSketch"

Draw Torque and Drag Charts

Figure XLV - Torque and Drag Calculator Computer Program Code Flow.

APPENDIX F

COMPUTER PROGRAMS

The flow of computer programs used for the Torque and Drag analyses is given in this section.

F.1 Torque and Drag Calculator Computer Program

The main computer program for the torque and drag calculator is as given below. The main computer program performs the execution of the mainframe computer run, and calls for the sub-programs to be executed accordingly. The main computer program and the sub programs eventually provide the overall torque and drag calculation for the bit depth inserted (performing the calculation for each and every single meter along the wellbore for each drill string item in the well) and then determines the maximum surface torque and lists this maximum torque in the archive list to estimate the torque for various depths along the wellbore.

```
Private Sub CommandButton3_Click()
'ARCHIVE OF THREE (3) POINTS IN THE WORKSHEET "Archive"
'ARCHIVE OF FIRST POINT IN THE WORKSHEET "Archive"
Sheets("ArchiveInteger").Range("b1").Value = TextBox4.Value
Sheets("WellName_Profile").Range("c9").Value
= Sheets("ArchiveInteger").Range("c1").Value

Call MDtoTVDCalcs
Call Create_1m_WellSketchData
Call CalculateUnitWtList
```

```
Call UnitWeighteCalculator
Call ODCreator
Call TorqueDragCalculationWellSketch
'UserForm5.Hide
'Unload UserForm5
'UserForm5.Show
Sheets("WellSketch").Select
 Range("A2").Select
    Range(Selection, Selection.End(xlToRight)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Sheets("Archive").Select
       Range("A1").Select
    Selection.End(xlDown).Select
    ActiveCell.Offset(1, 0).Activate ' move right 1 down
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
        Selection.End(xlToRight).Select
 ActiveCell.Offset(0, 1).Activate ' move right 1 right
ActiveCell.Value = Sheets("WellName_Profile").Range("b1").Value
ActiveCell.Offset(0, 1).Activate ' move right 1 right
ActiveCell.Value = Sheets("WellName_Profile").Range("d2").Value
' Get the Max Torque values for the first point
ActiveCell.Offset(0, -11).Activate ' move right 11 left
ActiveCell.Value = "=+MAX(WellSketch!O:O)"
 Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
ActiveCell.Offset(0, 1).Activate ' move right 1 right
ActiveCell.Value = "=+MAX(WellSketch!p:p)"
 Selection.Copy
```

```
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
ActiveCell.Offset(0, 7).Activate ' move right 7 left
ActiveCell.Value = "=+MAX(WellSketch!w:w)"
 Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
ActiveCell.Offset(0, 1).Activate ' move right 1 left
ActiveCell.Value = "=+MAX(WellSketch!x:x)"
 Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
'ARCHIVE OF SECOND POINT IN THE WORKSHEET "Archive"
Sheets("ArchiveInteger").Range("b2").Value = TextBox5.Value
Sheets("WellName_Profile").Range("c9").Value
= Sheets("ArchiveInteger").Range("c2").Value
Call MDtoTVDCalcs
Call Create_1m_WellSketchData
Call CalculateUnitWtList
Call UnitWeighteCalculator
Call ODCreator
Call TorqueDragCalculationWellSketch
'UserForm5.Hide
'Unload UserForm5
'UserForm5.Show
Sheets("WellSketch").Select
 Range("A2").Select
    Range(Selection, Selection.End(xlToRight)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Sheets("Archive").Select
```

```
       Range("A1").Select
     Selection.End(xlDown).Select
     ActiveCell.Offset(1, 0).Activate ' move right 1 down
         Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
         :=False, Transpose:=False
         Selection.End(xlToRight).Select
 ActiveCell.Offset(0, 1).Activate ' move right 1 right
ActiveCell.Value = Sheets("WellName_Profile").Range("b1").Value
ActiveCell.Offset(0, 1).Activate ' move right 1 right
ActiveCell.Value = Sheets("WellName_Profile").Range("d2").Value
' Get the Max Torque values for the 2nd point
ActiveCell.Offset(0, -11).Activate ' move right 11 left
ActiveCell.Value = "=+MAX(WellSketch!O:O)"
 Selection.Copy
     Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
         :=False, Transpose:=False
ActiveCell.Offset(0, 1).Activate ' move right 1 right
ActiveCell.Value = "=+MAX(WellSketch!p:p)"
 Selection.Copy
     Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
         :=False, Transpose:=False
ActiveCell.Offset(0, 7).Activate ' move right 7 left
ActiveCell.Value = "=+MAX(WellSketch!w:w)"
 Selection.Copy
     Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
         :=False, Transpose:=False
ActiveCell.Offset(0, 1).Activate ' move right 1 left
ActiveCell.Value = "=+MAX(WellSketch!x:x)"
 Selection.Copy
     Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
         :=False, Transpose:=False
```

```
'ARCHIVE OF THIRD POINT IN THE WORKSHEET "Archive"
Sheets("ArchiveInteger").Range("b3").Value = TextBox6.Value
Sheets("WellName_Profile").Range("c9").Value
= Sheets("ArchiveInteger").Range("c3").Value
Call MDtoTVDCalcs
Call Create_1m_WellSketchData
Call CalculateUnitWtList
Call UnitWeighteCalculator
Call ODCreator
Call TorqueDragCalculationWellSketch
UserForm5.Hide
Unload UserForm5
UserForm5.Show
Sheets("WellSketch").Select
 Range("A2").Select
    Range(Selection, Selection.End(xlToRight)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Sheets("Archive").Select
      Range("A1").Select
    Selection.End(xlDown).Select
    ActiveCell.Offset(1, 0).Activate ' move right 1 down
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
        Selection.End(xlToRight).Select
 ActiveCell.Offset(0, 1).Activate ' move right 1 right
ActiveCell.Value = Sheets("WellName_Profile").Range("b1").Value
ActiveCell.Offset(0, 1).Activate ' move right 1 right
ActiveCell.Value = Sheets("WellName_Profile").Range("d2").Value
' Get the Max Torque values for the 3rd point
ActiveCell.Offset(0, -11).Activate ' move right 11 left
```

```
ActiveCell.Value = "=+MAX(WellSketch!O:O)"
 Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
ActiveCell.Offset(0, 1).Activate ' move right 1 right
ActiveCell.Value = "=+MAX(WellSketch!p:p)"
 Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
ActiveCell.Offset(0, 7).Activate ' move right 7 left
ActiveCell.Value = "=+MAX(WellSketch!w:w)"
 Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
ActiveCell.Offset(0, 1).Activate ' move right 1 left
ActiveCell.Value = "=+MAX(WellSketch!x:x)"
 Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
End Sub
```

F.2 Interpolation Computer Program

The interpolation computer program is as given below. This code interpolates the data based on input range of data points for two data set (i.e. x and y data sets). The desired data point (i.e. x data point) to be interpolated is going to be determined between which two data points it falls, then the i.e. y magnitudes of the two input data points is going to be taken in linear calculation.

```
Private Sub Interpolation()
Dim num, num2, sayi, bul1, bul2, cvp, interpsayi As Long
```

```
       Range("H2").Select
   ActiveCell.FormulaR1C1 = "=COUNT(C[-7])"
   Range("I2").Select
   ActiveCell.FormulaR1C1 = "=COUNT(C[-4])"
    Range("h2").Select
  sayi = Range("h2").Value
      Range("i2").Select
  interpsayi = Range("i2").Value
  For num2 = 2 To interpsayi + 1
Application.ScreenUpdating = False
   Range("e" & num2).Select
  bul1 = Range("e" & num2).Value ' the number that is required to be interpolated
    For num = 2 To sayi + 1
Application.ScreenUpdating = False
     If Range("a" & num).Value > bul1 Then
bul1 = num - 1
Exit For
End If
Next num
bul2 = bul1 + 1
cvp = Range("b" & bul1).Value + (Range("e" & num2).Value - Range("a" & bul1).Value) * (Range("b" & bul2).Value - Range("b" & bul1).Value) / (Range("a" & bul2).Value - Range("a" & bul1).Value)
Range("f" & num2).Select
Range("f" & num2).Value = cvp
Next num2
Range("f2").Select
End Sub
```

F.3 MDtoTVDCalcs Computer Program

This code converts the MD depth data range into the TVD data range.

```
Sub MDtoTVDCalcs()
' MD to TVD Calculations for well Sketch data
Dim numSurvey, numCSGs As Integer
numSurvey = Sheets("Survey").Range("k1").Value + 1
numCSGs = Sheets("WellName_Profile").Range("d1").Value
' Copy the survey into the Interp Sheet
    Sheets("Interp-MD-to_TVD").Select
    Range("A2:B2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
    Range("A2").Select
    ActiveCell.Formula = "=+Survey!A2"
    Range("b2").Select
    ActiveCell.Formula = "=+Survey!D2"
   Range("A2:B2").Select
    Selection.Copy
    Range("A" & 3 & ":" & "B" & numSurvey & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
         ' Retrieve the CSG MD Depths and calculate the TVD depths: DEPTH START
    Sheets("Interp-MD-to_TVD").Select
    Range("e2:f2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
         Range("e2").Select
           ActiveCell.Formula = "=+WellName_Profile!B4"
                  Selection.Copy
```

```
        Range("E" & 3 & ":" & "E" & numCSGs + 1 & "").Select
       Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
 ' Retrieve the CSG MD Depths and calculate the TVD depths: DEPTH END
Range("e" & numCSGs + 2 & "").Select
         ActiveCell.Formula = "=+WellName_Profile!c4"
          Selection.Copy
Range("E" & numCSGs + 2 & ":" & "E" & 2 * numCSGs + 1 & "").Select
        Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False

'==============================================================
       ' INTERPOLATION MACRO
              Dim num, num2, sayi, bul1, bul2, cvp, interpsayi As Long
          Range("H2").Select
    ActiveCell.FormulaR1C1 = "=COUNT(C[-7])"
    Range("I2").Select
    ActiveCell.FormulaR1C1 = "=COUNT(C[-4])"
      Range("h2").Select
   sayi = Range("h2").Value
         Range("i2").Select
   interpsayi = Range("i2").Value
   For num2 = 2 To interpsayi + 1
Application.ScreenUpdating = False
    Range("e" & num2).Select
   bul1 = Range("e" & num2).Value ' the number that is required to be interpolated
      For num = 2 To sayi + 1
Application.ScreenUpdating = False
       If Range("a" & num).Value > bul1 Then
bul1 = num - 1
Exit For
```

```
End If
Next num
bul2 = bul1 + 1
cvp = Range("b" & bul1).Value + (Range("e" & num2).Value - Range("a" & bul1).Value) * (Range("b" & bul2).Value - Range("b" & bul1).Value) / (Range("a" & bul2).Value - Range("a" & bul1).Value)
Range("f" & num2).Select
Range("f" & num2).Value = cvp
Next num2
Range("f2").Select
'=============================================================
' COPY THE TVD From Interp to WELLNAME_PROFILE
Range("f" & 2 & ":" & "f" & numCSGs + 1 & "").Select
Selection.Copy
Sheets("WellName_Profile").Select
Range("h" & 4 & ":" & "h" & numCSGs + 3 & "").Select
  Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
        Sheets("Interp-MD-to_TVD").Select
     Range("f" & numCSGs + 2 & ":" & "f" & 2 * numCSGs + 1 & "").Select
Selection.Copy
Sheets("WellName_Profile").Select
Range("i" & 4 & ":" & "i" & numCSGs + 3 & "").Select
  Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
End Sub
```

F.4 Create_1m_WellSketchData Computer Program

The dataset is arranged so that the every 1 m interval of the wellbore from surface to the given bit depth is created for the calculations.

```
Sub Create_1m_WellSketchData()
Dim derinliksayisi, numbb As Integer
Sheets("WellSketch").Select
Range("A2").Select
     Range(Selection, Selection.End(xlToRight)).Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
    Range("A2").Select
        derinliksayisi = Sheets("WellName_Profile").Range("f1").Value
    'Sheets("WellSketch").Range("a2").Value = derinliksayisi
    For numbb = 0 To derinliksayisi
    Application.ScreenUpdating = False
    Range("a" & numbb + 2 & "").Value = numbb
    Range("b" & numbb + 2 & "").Value = numbb + 0.001
    Next numbb
        Dim numSurvey As Integer
numSurvey = Sheets("Survey").Range("k1").Value + 1
'==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0
' CREATE THE INCLINATION DATABASE
    Sheets("Interp-Inc").Select

Range("A2:B2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
    Range("A2").Select
    ActiveCell.Formula = "=+Survey!A2"
    Range("b2").Select
    ActiveCell.Formula = "=+Survey!b2" 'Select Inclination in this line
   Range("A2:B2").Select
    Selection.Copy
    Range("A" & 3 & ":" & "B" & numSurvey & "").Select
```

```
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
         Range("e2:f2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
        Range("e2").Select
    ActiveCell.Formula = "=+WellSketch!A2"
    Selection.Copy
    Range("e" & 3 & ":" & "e" & derinliksayisi + 2 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False

'================================================================
       ' INTERPOLATION MACRO

        Dim num, num2, sayi, bul1, bul2, cvp, interpsayi As Long
          Range("H2").Select
    ActiveCell.FormulaR1C1 = "=COUNT(C[-7])"
    Range("I2").Select
    ActiveCell.FormulaR1C1 = "=COUNT(C[-4])"
      Range("h2").Select
   sayi = Range("h2").Value
         Range("i2").Select
   interpsayi = Range("i2").Value
   For num2 = 2 To interpsayi + 1
Application.ScreenUpdating = False
    Range("e" & num2).Select
   bul1 = Range("e" & num2).Value ' the number that is required to be interpolated
      For num = 2 To sayi + 1
Application.ScreenUpdating = False
       If Range("a" & num).Value > bul1 Then
```

```
bul1 = num - 1
Exit For
End If
Next num
bul2 = bul1 + 1
cvp = Range("b" & bul1).Value + (Range("e" & num2).Value - Range("a" & bul1).Value) * (Range("b" & bul2).Value - Range("b" & bul1).Value) / (Range("a" & bul2).Value - Range("a" & bul1).Value)
Range("f" & num2).Select
Range("f" & num2).Value = cvp
Next num2
Range("f2").Select
'==============================================================

    Sheets("WellSketch").Select
    Range("c2").Value = "=+'Interp-Inc'!F2"
   Range("c2").Select
    Selection.Copy
 Range("c" & 3 & ":" & "c" & derinliksayisi + 2 & "").Select
     Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
'==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0
' CREATE THE AZIMUTH DATABASE

    Sheets("Interp-Azm").Select

Range("A2:B2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
    Range("A2").Select
    ActiveCell.Formula = "=+Survey!A2"
```

```
    Range("b2").Select
    ActiveCell.Formula = "=+Survey!c2" 'Select Azimuth in this line
   Range("A2:B2").Select
    Selection.Copy
    Range("A" & 3 & ":" & "B" & numSurvey & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False

Range("e2:f2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
    Range("e2").Select
    ActiveCell.Formula = "=+WellSketch!A2"
    Selection.Copy
    Range("e" & 3 & ":" & "e" & derinliksayisi + 2 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False

'============================================================
Call AZMINTERP
'============================================================
    Sheets("WellSketch").Select
    Range("d2").Value = "=+'Interp-Azm'!F2"
   Range("d2").Select
    Selection.Copy
 Range("d" & 3 & ":" & "d" & derinliksayisi + 2 & "").Select
     Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
'==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0==0
           End Sub
```

F.5 ODCreator Computer Program

The OD creator computer program determines the OD and ID range for each and every 1 m interval of the drill string.

```
Sub ODCreator()
Dim datapoints, bhaelemansayisi As Integer
Sheets("OD_Creator").Select
Range("a3:b3").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
Range("a3").Value = "=+BHA!g2"
Range("b3").Value = "=+BHA!c2"
Range("a3:b3").Select
bhaelemansayisi = Sheets("BHA").Range("n1").Value
Selection.Copy
 Range("a" & 4 & ":" & "b" & bhaelemansayisi + 2 & "").Select
     Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
    Range("M3:N3").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
datapoints = Range("o1").Value
For num = 3 To datapoints + 2
    Range("M" & (num - 1) * 2 & "").Select
    ActiveCell.FormulaR1C1 = Range("a" & num & "").Value
        ActiveCell.Offset(1, 0).Activate
    ActiveCell.FormulaR1C1 = "=+R[-1]C"
    ActiveCell.Value = ActiveCell.Value + 0.0001
            Range("N" & (num - 1) * 2 & "").Select
    ActiveCell.FormulaR1C1 = Range("b" & num & "").Value
```

```
        ActiveCell.Offset(1, 0).Activate
    ActiveCell.FormulaR1C1 = "=+R[+1]C"
Next num
    Range("M3").Select
    ActiveCell.FormulaR1C1 = "0"
           Range("N3").Select
    ActiveCell.FormulaR1C1 = "=+R[1]C"
        Range("M" & 2 * datapoints + 3 & ":N" & 2 * datapoints + 3 & "").Select
Selection.ClearContents
Range("M1").Select
'0000000000000000000000
Sheets("Interp-OD").Select
Range("A2").Select
     Range(Selection, Selection.End(xlToRight)).Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
    Range("A2").Value = "=+OD_Creator!M3"
Range("b2").Value = "=+OD_Creator!n3"
   Range("A2:B2").Select
    Selection.Copy
    Range("A" & 2 & ":" & "B" & 2 * datapoints + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
Range("A" & 2 * datapoints + 1 & "").Value = Range("A" & 2 * datapoints + 1 & "").Value + 0.0001
'============================================================
       ' INTERPOLATION MACRO
        Dim numaa, num2, sayi, bul1, bul2, cvp, interpsayi As Long
          Range("H2").Select
    ActiveCell.FormulaR1C1 = "=COUNT(C[-7])"
    Range("I2").Select
```

```
    ActiveCell.FormulaR1C1 = "=COUNT(C[-4])"
      Range("h2").Select
   sayi = Range("h2").Value
         Range("i2").Select
   interpsayi = Range("i2").Value
   For num2 = 2 To interpsayi + 1
Application.ScreenUpdating = False
    Range("e" & num2).Select
   bul1 = Range("e" & num2).Value ' the number that is required to be interpolated
      For numaa = 2 To sayi + 1
Application.ScreenUpdating = False
       If Range("a" & numaa).Value > bul1 Then
bul1 = numaa - 1
Exit For
End If
Next numaa
bul2 = bul1 + 1
cvp = Range("b" & bul1).Value + (Range("e" & num2).Value - Range("a" &
bul1).Value) * (Range("b" & bul2).Value - Range("b" & bul1).Value) / (Range("a" &
bul2).Value - Range("a" & bul1).Value)
Range("f" & num2).Select
Range("f" & num2).Value = cvp
Next num2
Range("f2").Select
'==========================================================
    Range("f" & 2 & ":" & "f" & interpsayi + 1 & "").Select
Selection.Copy
Sheets("WellSketch").Select
    Range("m2").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
```

```
End Sub
```

F.6 CalculateUnitWtList Computer Program

The unit weight list for each and every 1 m interval listed is going to be calculated using the below code in order to perform the Torque and Drag calculations by means of calculating the Unit Weight using the OD and ID information available.

```
Sub CalculateUnitWtList()
Dim derinliksayisi, numbb As Integer
Sheets("UnitWt_Cal").Select
Range("A2").Select
     Range(Selection, Selection.End(xlToRight)).Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
    Range("A2").Select
        derinliksayisi = Sheets("WellName_Profile").Range("f1").Value
    'Sheets("WellSketch").Range("a2").Value = derinliksayisi
    For numbb = 0 To derinliksayisi
    Application.ScreenUpdating = False
    Range("a" & numbb + 2 & "").Value = numbb
    Range("b" & numbb + 2 & "").Value = numbb + 0.001
    Next numbb
    Selection.End(xlDown).Select
    ActiveCell.Value = ActiveCell.Value + 0.0001
    End Sub
```

F.7 TorqueDragCalculationWellSketch Computer Program

This program ensures that the well sketch worksheet of the program is going to be updated accordingly for each and every run of the torque and drag calculation.

```
Sub TorqueDragCalculationWellSketch()
Sheets("WellSketch").Select
Dim derinliksayisi As Integer
derinliksayisi = Sheets("WellName_Profile").Range("f1").Value
   Range("A2").Select
   Range(Selection, Selection.End(xlToRight)).Select
   Range(Selection, Selection.End(xlDown)).Select
   Selection.Copy
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Application.CutCopyMode = False
   ActiveWorkbook.Worksheets("WellSketch").Sort.SortFields.Clear
   ActiveWorkbook.Worksheets("WellSketch").Sort.SortFields.Add Key:=Range( _
      "A2:A" & derinliksayisi + 2 & ""), SortOn:=xlSortOnValues,
Order:=xlDescending, DataOption:= _
      xlSortNormal
   With ActiveWorkbook.Worksheets("WellSketch").Sort
      .SetRange Range("A1:E" & derinliksayisi + 2 & "")
      .Header = xlYes
      .MatchCase = False
      .Orientation = xlTopToBottom
      .SortMethod = xlPinYin
      .Apply
   End With
Dim muddensity As Double
muddensity = Sheets("WellName_Profile").Range("h1").Value
Sheets("WellSketch").Range("F2:F" & derinliksayisi + 2 & "").Value = muddensity
Sheets("WellSketch").Range("g2").Value = "=1-F2*8.33/65.5"
Range("G2").Select
   Selection.Copy
     Range("G3:G" & derinliksayisi + 2 & "").Select
```

```
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
    'SECTION BUOYED WEIGHT CALC
Sheets("WellSketch").Range("h2").Value = "=+(A2-A3)*3.28*E2*G2"
Range("h2").Select
    Selection.Copy
       Range("h3:h" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
    'SECTION Fnormal CALC
Sheets("WellSketch").Range("i2").Value = "=+SIN((RADIANS(C2)))*H2"
Range("i2").Select
    Selection.Copy
       Range("i3:i" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
 'SECTION FF CALC
Sheets("WellSketch").Range("j2").Value                                    =
"=+IF(A2>WellName_Profile!$J$1,WellName_Profile!$N$1,WellName_Profile!$L$1)
"
Range("j2").Select
    Selection.Copy
       Range("j3:j" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
 'SECTION Fnormal*FF, lbs CALC
Sheets("WellSketch").Range("k2").Value = "=+I2*J2"
Range("k2").Select
    Selection.Copy
       Range("k3:k" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
```

```
        SkipBlanks:=False, Transpose:=False
 'SECTION Cumulative Drag(noAzmCor), lbs CALC
Sheets("WellSketch").Range("l2").Value = "=+K2"
Sheets("WellSketch").Range("l3").Value = "=+L2+K3"
Range("l3").Select
    Selection.Copy
       Range("l3:l" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
   Call ODCreator
 'SECTION Section Torque, lbs.ft CALC
Sheets("WellSketch").Range("n2").Value = "=+M2/2*K2/12"
Range("n2").Select
    Selection.Copy
       Range("n3:n" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
 'SECTION Cumulative Non drilling Torque (noAzmCor), lbs.ft CALC
Sheets("WellSketch").Range("o2").Value = "=+n2"
Sheets("WellSketch").Range("o3").Value = "=+o2+n3"
Range("o3").Select
    Selection.Copy
       Range("o3:o" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
 'SECTION Cumulative Drilling(noAzmCor), lbs.ft CALC
Sheets("WellSketch").Range("p2").Value = "=+O2+WellName_Profile!$P$1"
Range("p2").Select
    Selection.Copy
       Range("p3:p" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
```

```
        SkipBlanks:=False, Transpose:=False
 'SECTION Delta Azm, deg CALC
Sheets("WellSketch").Range("q2").Value = "=D2-D3"
Range("q2").Select
    Selection.Copy
       Range("q3:q" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
 'SECTION Section Faxial, lbs CALC
Sheets("WellSketch").Range("r2").Value = "=+H2*COS(RADIANS(C2))"
Range("r2").Select
    Selection.Copy
       Range("r3:r" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
 'SECTION Section Fnormal, lbs CALC
Sheets("WellSketch").Range("s2").Value = "=+((R2*(Q2)*SIN(RADIANS(C2)) )^2    +
(H2*R2*(Q2)*SIN(RADIANS(C2)) )^2      )^0.5"
Range("s2").Select
    Selection.Copy
       Range("s3:s" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
 'SECTION Cumulative Section Fnormal, lbs CALC
Sheets("WellSketch").Range("t2").Value = "=+s2"
Sheets("WellSketch").Range("t3").Value = "=+t2+s3"
Range("t3").Select
    Selection.Copy
       Range("t3:t" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
```

```
 'SECTION Cumulative Faxial while UpMove (Azm Correction), lbs CALC
Sheets("WellSketch").Range("u2").Value = "=+(R2+J2*S2)"
Sheets("WellSketch").Range("u3").Value = "=+(R3+J3*S3)+U2"
Range("u3").Select
    Selection.Copy
       Range("u3:u" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
   'SECTION Section Fnormal, lbs CALC
Sheets("WellSketch").Range("v2").Value = "=+M2*J2*S2/12/2"
Range("v2").Select
    Selection.Copy
       Range("v3:v" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
 'SECTION Cumulative Non drilling Torque (AzmCor), lbs.ft CALC
Sheets("WellSketch").Range("w2").Value = "=+v2"
Sheets("WellSketch").Range("w3").Value = "=+w2+v3"
Range("w3").Select
    Selection.Copy
       Range("w3:w" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
'SECTION Cumulative Drilling(AzmCor), lbs.ft CALC
Sheets("WellSketch").Range("x2").Value = "=+w2+WellName_Profile!$P$1"
Range("x2").Select
    Selection.Copy
       Range("x3:x" & derinliksayisi + 1 & "").Select
    Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
 End Sub
```