Sudan University of Science and Technology

College of Petroleum Engineering and Technology

Petroleum Engineering Department

Project Title:

Modelling of Torque and Drag in Extended Reach Drilling Using Landmark Software

(Case Study a well in Field X, Block 2B)

محاكاة العزم والسحب في الحفر الممتد لمسافة بعيدة بإستخدام برنامج Landmark

(دراسة حالة لبئر في حقل X، مربع 2B)

Submitted in Partial Fulfillment of the Requirements of the Degree of B.Sc. in Petroleum Engineering

This Project is a Property of:

- Al-basheir Khidir Basheir Al-haj
- Al-Daow Mohammed Al-Daow
- Omer Ahmednour Abdulrahman
- Mohanad Mubarak Yosuf Mubarak

Supervisor:

Dr. Mohamed Ahmed Mohamed Naiem

October 2015

Opening

بسم الله الرحمن الرحيم

قال تعالى:

(نرفع درجات من نشاء وفوق كل ذي علم عليم)

سورة يوسف الأية (76)

قال صلي الله عليه وسلم :

(لا يزال المرء عالماً ما دام يطلب العلم فإن ظن أنه علم فقد جهل)

Dedication

To the spirit of our father, brother, teacher, and academic supervisor Dr. Mohamed Ahmed Mohamed Naiem for his kindness, gentleness, and generous. We won't stop asking Allah for him to forgive him and give him the highest levels of the paradise.

To our fathers and mothers who taught us great lessons about life, guiding, motivation, innovation and support us along life's level.

Without them we would not become the people who we are today.

To our brothers and sisters who stand with us, encourage us and taught us the real meaning of helping other people with all we have.

For future generations that hold future of the oil industry in Sudan.

We are honor to offer you this modest work.

Thanks all for giving us a chance to prove and improve our self through all levels of university life.

Acknowledgment

Several sources of information have been used to make this project. We would like to express our sincere gratitude and appreciation to our academic supervisor, Dr. Mohamed Ahmed Mohamed Naiem for his consistent advice and receptiveness to opinions and ideas while we worked on this project.

We would like to give a special thanks to Dr. Yousif Bagadi for his support and guidance. Also a special thanks goes to Dr. Elham Mohammed Mohammed Khair. Very special Thanks goes to Abdalmjeed Habeeballah, M.Sc Student at KFU, who inspired us to work in this project.

A lot of credit goes to Mohammed Elrashied, Drilling Engineer, Ahmed Eldusogi Mohamed, Financial Insp., Rifat Mohamed Elnour, Drilling Engineer, Abdelmoneim Mohamed Ahmed Mohamed, Geologist, Sumia Aljuzuli Alamin, Geologist, who encouraged us and with their support and guidance we have been able to get some of the data we need to carry out this project.

Also, we would like to thank Hassan Abdallah, Drilling Engineer, for his academic support. Of course we did not forget to thank Dr. Ahmed Abdalaziz Ebraheem for his technical support.

To all whose names have been mentioned and those not mentioned, we say THANKS is a small word, but it goes a long way to show how much we appreciate your love, care and concern while we worked on this project.

Abstract

The interest in torque and drag (T&D) issues has over the last years increased when the complexity of wells drilled become higher. Excessive drillstring T&D is one of the major limitations of extended reach drilling. The T&D models are used in the planning phase and during the drilling of a well, as a tool used for monitoring developing hole problems.

In this project, T&D modelling process have been performed on a horizontal well, ABMO-1 horizontal well, located in field X, block 2b using Landmark software. The modelling process have been performed in three steps: first, the correct friction factor for cased hole section has been calculated from actual field data while the friction factor for openhole section has been assumed due to lack of sufficient actual data; second, the measured weights encountered during the drilling of the well have been matched with actual weight data; then T&D have been analyzed.

Then, the horizontal section of ABMO-1 horizontal well has been assumed to be extended to form ABMO-1 ERD well and T&D have been analyzed to determine how long this well could be extended in the horizontal section without significant T&D problems in addition to determine the maximum weights and torques to be encountered during the drilling of ABMO-1 ERD well and therefore, determine the capability of the required drilling rig.

The modelling results show that the ABMO-1 ERD well can be drilled using the same rig used to drill ABMO-1 horizontal well because the weights and torques to be encountered during drilling of ABMO-1 ERD well fall within the rig capability.

*Key Words***:** *Torque, Drag, Friction Factor***,** *Modelling***,** *Landmark.*

التجريد

التطور المستمر للصناعة النفطية ينتج عنه تطور في الآبار المحفورة وتعقيد أشكالها. تزداد المشاكل المتعلقة بحفر الآبار بزيادة طول الآبار و تعتبر المشاكل المتعلقة بالقوة الدورانية التي يجب تسليطها علي عمود الحفر من السطح (العزم) وكذلك مشاكل الإختلاف في الوزن بين عمود الحفر وهو في البئر و عند رفعه الي أعلي أو إنزاله إلي أسفل (السحب) من أكبر المشاكل في الآبار ذات الأشكال المعقدة وخاصة الآبار المحفورة لمسافات أفقية بعيدة لأن هذه القوي يمكن أن تحد من قابلية البئر للحفر. لذلك أصبح الإهتمام بالبرامج التي تتيح عملية محاكاة العزم والسحب متزايداً لأنها تتيح مراقبة البئر أثناء الحفروبالتالي التنبؤ بالمشاكل التي تحدث أثناء الحفر.

في هذا البحث تم إجراء عملية محاكاة العزم والسحب لبئر أفقية (ABMO-1 horizontal well) في حقل (X) مربع (2B) باستخدام برنامج Landmark. تم إجراء عملية المحاكاة في ثلاثة خطوات: أولاً، بما أن معامل الإحتكاك يلعب دوراً مهما في العزم والسحب، تم حساب هذا المعامل للجزء المبطن من البئر بإستخدام بيانات حقلية حقيقية ولكن نتيجة لشح البيانات المتوفرة، تم فرض قيمة هذا المعامل للجزء غير المبطن من البئر؛ ثانياً، تم إدخال أوزان عمود الحفر التي تم قياسها أثناء عملية حفر البئر وفي ظروف مختلفة لبرنامج Landmark و تمت مطابقتها مع الأوزان المحسوبة بواسطة البرنامج؛ ثالثاً، تم تحليل العزم والسحب لهذه البئر.

بعد ذلك تم إفتراض أن المقطع الأفقي للبئر (ABMO-1 horizontal well) تم تمديده بحيث أن البئر الناتجة (ABMO-1 ERD well) تصبح بئر ممتدة لمسافة بعيدة في المقطع الأفقي وتم إجراء عملية محاكاة العزم والسحب لهذه البئر في سبيل معرفة قابلية البئر للحفر و معرفة المسافة الأفقية التي يمكن زيادتها في المحور الأفقي قبل حصول مشاكل في العزم والسحب تحد من قابلية حفر البئر. أيضا تم حساب أوزان عمود الحفر وكذلك قيم العزم المتوقعة عند حفر البئر في الظروف المختلفة من أجل تحديد إمكانيات الحفارة المطلوبة.

نتائج المحاكاة أظهرت أن البئر الممتدة في المقطع الأفقي (ABMO-1 ERD well) يمكن أن تحفر بإستخدام نفس الحفارة التي أستخدمت لحفر البئر الأفقية (ABMO-1 horizontal well) بناءا علي الأوزان والعزوم المتوقعة أثناء حفر البئر.

كلمات مفتاحية: *العزم، السحب، معامل الإحتكاك، المحاكاة، Landmark.*

List of Contents

Chapter 1: Introduction

Chapter 2: Literature Review and Theoretical Background

Chapter 3: Methodology

Chapter 4: Results and Discussion

Chapter 5: Conclusions and Recommendations

List of Figures

List of tables:

Nomenclature:

ERD	Extended Reach Drilling
MD	Measured Depth
TVD	True Vertical Depth
HD	Horizontal displacement
TD	Total Depth
T&D	Torque and Drag
BHA	Bottom Hole Assembly
ERW	Extended Reach Well
DLS	Dog Leg Severity
WOB	Weight on Bit
BWOB	Downhole Weight on Bit
DTOB	Downhole Torque on Bit
RIH	Running In Hole
POOH	Pulling Out Of Hole
WBM	Water Based Mud
OBM	Oil Based Mud
MWD	Measurements While Drilling
HWDP	Heavy Weight Drill Pipe
ROP	Rate of Penetration
RPM	Revolution per Minute
RSS	Rotary Steerable System
2D	Two Dimensional
3D	Three Dimensional
EDM	Engineer’s Data Model
TDA	Torque Drag analysis
PRS	Pickup/Rotate/slack off

Chapter One

Introduction

1.1 Extended Reach Drilling:

Extended reach drilling (ERD) is essentially an advanced form of directional drilling, it has evolved from simple directional drilling to horizontal, lateral, and multilateral (Gerding, 1986). ERD can be defined as an integrated methodology for drilling high-angle wellbores with long horizontal displacements. ERD wells are typically kicked off from the vertical near the surface and built to an angle of inclination that allows sufficient horizontal displacement from the surface to the desired target. This inclination is held constant until the wellbore reaches the zone of interest and is then kicked off near the horizontal and extended into the reservoir (Al-Suwaidi, El- Nashar, Allen and Brandao, 2001). This technology enables:

- Optimization of field development through the reduction of drilling sites and structures,
- Allows the operator to reach portions of the reservoir at a much greater distance than it is possible with conventional directional drilling technology.

ERD wells are generally associated with accessing reservoirs at locations remote from a drill site. Generally, a well is defined as extended reach if it has a step out Ratio of 2 or more. Step out Ratio is defined as the measured depth (MD) divided by the true vertical depth (TVD) at total depth (Economides, Watters, and Dun-Norman, 1998).

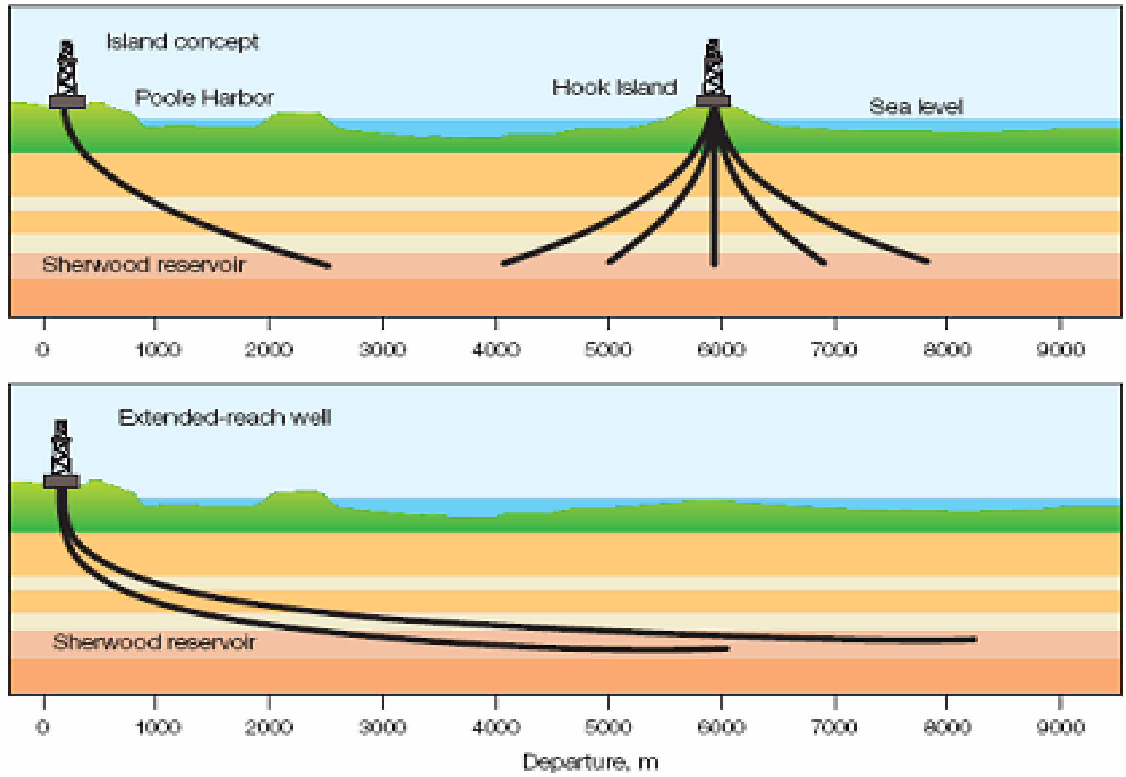


Fig.1.1: Comparison between Conventional Directional Drilling and ERD (E-Tech International, 2005).

Since ERD is associated with long horizontal departures, there are many factors that are considered as a critical technologies for success of an ERD well. Based on the many lessons learned in recent projects, technologies that have been identified to be vital to the success of ERD (Payne, Cocking and Hatch, 1994) include the following:

- Torque and drag (T&D);
- Drillstring and bottom hole assembly (BHA) design;
- Wellbore stability (Planning and monitoring);
- Hydraulics and hole cleaning (Rate, Rheology, Rotation);
- Casing considerations;
- Solids control;
- Directional well planning;
- Directional drilling optimization;
- Survey planning and accuracy limitations;
- Drilling dynamics;

- Rig sizing and selection (Top-drive, mud pumps, power);

T&D are considered as a limiting factors for success of an ERD well because the drillability of an ERD well depends on T&D limits reached. In ERD, a limitation on the HD occurs because of frictional forces between the drillstring and the borehole wall. Drag is measured as the difference between the static weight of the drillstring and the tripping weight. Similarly, a difference between the torque applied at the rig floor and the torque available at the bit occurs owing to friction. T&D problems are often associated with each other and may be profound in ERD wells. This makes the accurate prediction of T&D very essential (Aarrestad and Blikra, 1994).

T&D modelling is required in well planning because it helps to predict and prevent drilling problems that might occur during the drilling process. Thus, T&D modelling is regarded as an invaluable process to assist in well planning and to predict and prevent drilling problems. It discusses how to use T&D calculations and measurements to plan ERD wells profiles, to execute drilling operations that minimize T&D effects and to monitor hole cleaning. The increased T&D could be due to ineffective hole cleaning, hole instability, differential sticking and solids in the mud system or the wellbore geometry (Mirhaj, 2011).

Hence, it is factual to say that T&D predictions are critical when planning an ERD well. Since the T&D limits reached during the drilling of an ERD well determines the ability to drill the well, T&D and T&D modelling will be explained in more details in the next chapters of this project.

1.2 Statement of the Problem:

Since excessive T&D can be critical limitation in ERD, T&D modeling is regarded as an invaluable process to assist in well planning and to predict and prevent drilling problems. T&D modelling is required in well planning process because it helps to predict and prevent drilling problems that might occur during the drilling process.

Herein this project, a horizontal well located in block 2b, field X is selected as case study to perform T&D analysis. Then this horizontal well is assumed to be completed into an ERD well through extending the horizontal section of this well. Then, landmark software, which involves T&D module, is used to model T&D for this well in order to analyze the drillability of this well and determine how long this well could be extended in the horizontal section before significant problems such as mechanical limitations of the drilling rig and drillstring start to occur.

The modelling results, when compared with the field measurements of T&D, can be used to predict and prevent the problems that might occur during the drilling process of this well.

1.3 Objectives:

The objectives of this project is divided into two groups, general and specific objectives. The general objectives of this project include the following:

1- To explain in details the concept of T&D and the factors affect it.

2- To explain in details the T&D modelling process and take a review on the previous works.

The specific objective of this project is to perform T&D modelling process on a horizontal well, ABMO-1 horizontal well, located in field X, block 2b. T&D modelling for this well include matching process between the actual or measured weights encountered during the drilling of this well and calculated weights using landmark software.

Then, the ability to convert this horizontal well into an ERD well, drilliability of this well, will be analyzed to know how long this well could be extended in the horizontal section without significant T&D problems.

1.4 Methodology:

The project work is broken into the following parts:

1- An 5428ft true vertical depth (TVD), 7767ft measured depth (MD),3352ft horizontal displacement (HD) horizontal well located in block 2b, field X is chosen as a case study for this project to perform T&D modelling process using Landmark software.

2- Then, the ability to convert this horizontal well into an ERD well through extending the horizontal section will be investigated to know how long this horizontal well could be extended in the horizontal section without significant T&D problems. The drillability analysis will be done after performing some accepted modifications into the original horizontal well include the following:

- For an ERD well, the ratio between the MD and TVD should be at least 2. This dictates that the horizontal well must be extended in the horizontal section, in order to be an ERD well, by about 3280ft.
- Some accepted modifications to the drill string have been performed in order to be suitable with the new assumed ERD well.

The well is now considered an ERD well, thus we can model or simulate T&D for this well using Landmark software and the modelling results, when compared with the field measurements could be useful in prediction and prevention of the drilling problems if the well is converted to an ERD well in reality.

Chapter two

Literature Review and Theoretical Background

2.1 Literature Review:

Torque and drag (T&D) are the key aspects in the planning and operational phases of an ERD well. A poor understanding of the T&D issues in ERD well is the main reason of failures in most cases. T&D modelling is required in well planning because it helps to predict and prevent drilling problems that might occur during the drilling process.

Excessive T&D now often present significant obstacles to the successful drilling of today's ERD wells. Without an accurate assessment of the well prior to drilling, the risk is increased that drilling or running casing to the total depth (TD) might not be feasible. With this in mind equations were developed to predict frictional forces and their impact on well operations as early as 1980's.

The fundamental T&D model was developed by Johancsik et al. in 1984 and formalized by Sheppard et al. in 1987. Since then, T&D software has been utilized by the oil and gas industry. The equations in T&D models have not changed significantly since their establishment (McCormick, Melissa and Chiu, 2011).

2.1.1 Soft String Model:

Most common T&D software programs available are variations of the soft string model developed by Johancsik et al. A soft string model assumes that the entire drill string lies against the wellbore, Fig.2.1, and the stiffness of the drill string is not accounted for. The drill string is modeled as a cable that is divided up into small elements, Fig.2.2, that only carry axial loads and torque; contact forces are supported by the wellbore. The forces on the elements consist of tension, compression, and torsion that cumulatively build from the bottom of the string to the surface. In other words, T&D are calculated by assuming the segments of the T&D generated from bottom of the string to the surface.

Johancsik assumed both T&D to be caused entirely by sliding friction forces that result from contact of the drillstring with the wellbore. He then defines the sliding friction force to be a function of the normal contact force and the coefficient of friction between the contact surfaces based on Coulomb's friction model. He wrote the force balance for an element of the pipe considering the fact that the normal component of tensile force acting on the element contributing to the normal force. Of course this is not the case for a straight section like in hold section (Mirhaj, 2011).

Soft string models disregard the bending moments caused by the stiffness of the pipe and radial clearance of the drill string. Some argue that the accuracy of the soft string model is degraded because of the model ignores the stiffness in the string. However, depending on the well situation, the soft string model may be closer to field data than stiff string model or vice versa (McCormick, Melissa and Chiu, 2011).

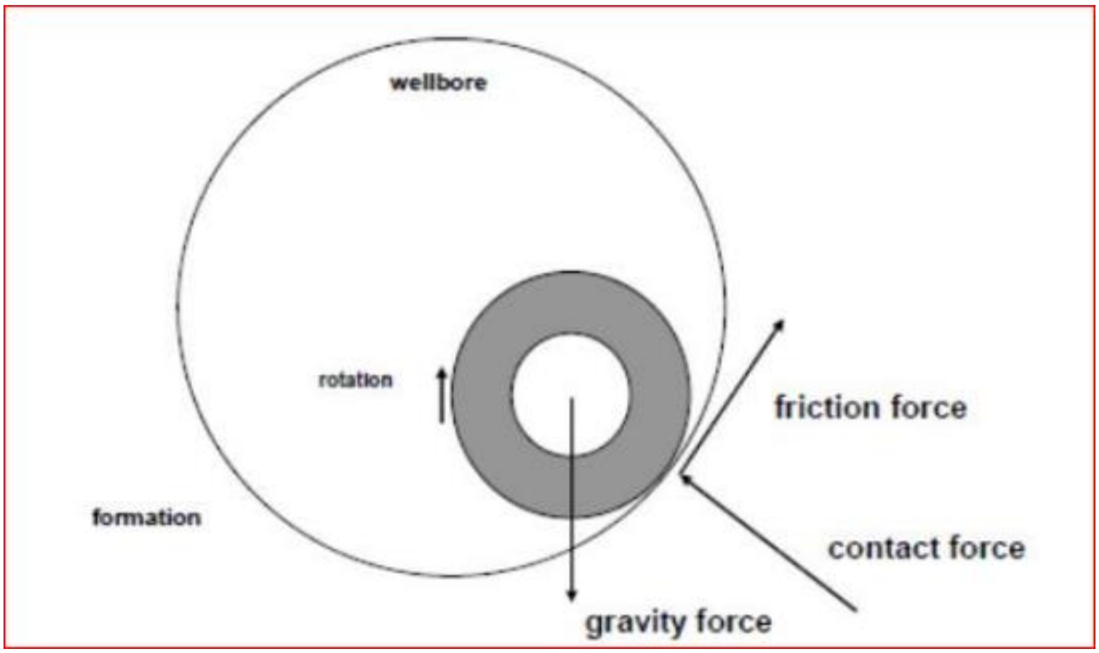


Fig.2.1: Drillstring Rotating Equilibrium Position (Mitchell and Samuel, 2007).

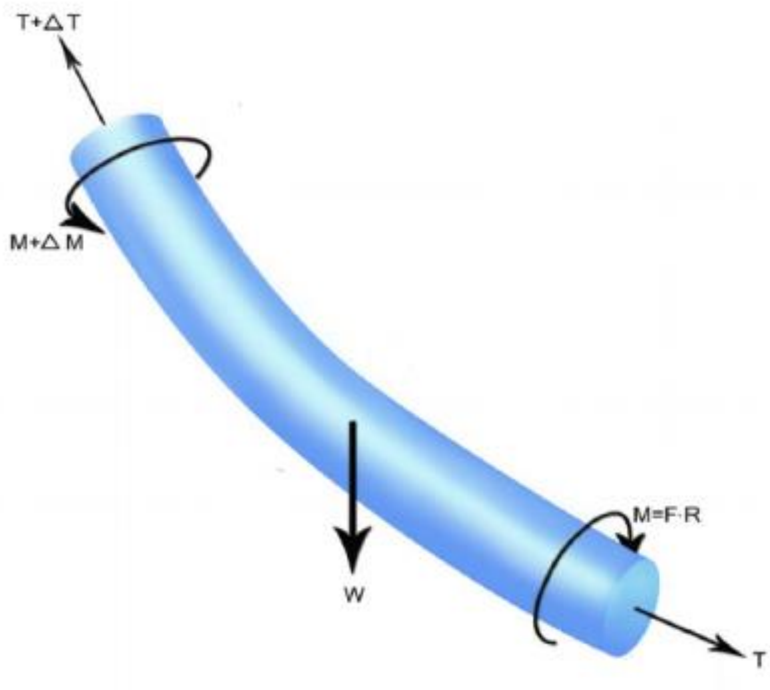


Fig.2.2: Short Element in a String (McCormick, Melissa and Chiu, 2011).

2.1.2 Stiff String Model:

In addition to soft string models, stiff string T&D models have also been developed. One major distinction between the soft string model and the stiff string model is that instead of treating the pipe as small elements of a cable, it accounts for the actual stiffness of the string.

The stiff string model takes into consideration the bending moment in the tubular and radial clearance in the wellbore. Stiff string models are most beneficial when wells that have high tortuous trajectories, high dogleg severity, or stiff tubulars. The stiff string model is more complex compared to the soft string model because of the additional inputs and calculations needed to account for various bending forces.

A greater variety of numerical methods including finite difference, finite element and semi analytical techniques are employed in the stiff string modeling programs. It attempts to give a more realistic T&D analysis on more difficult well. Nevertheless, it is hard to accurately account for tubular bending forces and radial clearance (Mason, 2007).

Later Sheppard et al. (1987) put the Johancsik's model into standard differential form and also took the mud pressure into account that acts upward when the drillstring is running inside hole. In other words he put effective tension instead of true tension and defined the effective tension as the sum of the true tension and mud pressure. He used this concept and showed that an under section trajectory could have reduced friction compared to a conventional tangent section. He also suggested that to put T&D into two categories separately; one caused by poor hole conditions and improper mud weight and the other associated with well path

Maidla and Wojtanowicz (1987) presented a method to evaluate an overall friction coefficient between the wellbore and the casing string. The computation is based on matching field data and modeling by assuming a friction coefficient.

Bret et al. (1989) used the johancsik's model for a field case and based on the model, a well is planned first and it has been used to monitor hole conditions by back-calculating apparent friction coefficients through the whole well interval and sections with large increase in friction factor expresses the fact that a problem existing in the wellbore which could whether be due to hole geometry or to some other factors. Then he used the model to identify drilling problems by analyzing the previously drilled well and using the information gained for a better wellbore trajectory, changing of mud type and casing setting depth, raising and lowering of the kick-off point to reduce T&D required to drill the wellbore and changing the place of bottom hole assembly to optimize forces in the wellbore.

Ho (1988) improved Johancsik soft-string model into somehow stiff-string and showed that for most parts of the drillstring the stiffness effect like drillpipe, heavy-wall drillpipe is minor and for drillcollars is major and has to be taken into account. Payne et al. (1998) describes concerns regarding torque and drag considerations including buckling, cuttings bed and wellbore trajectory.

Opeyemi et al. (1998) perform both well planning and drillstring design by using a T&D analysis with considering all constrains might be encountered during planning phase. He also suggests that the T&D model which is used for planning and modeling processes should be updated with the dynamics of the field operation by performing drilling, tripping and frictional sensitivity analysis. This will ensure more precise understanding of wellbore and drillstring interactions from surface to total depth (TD).

Feiber et al. (1999) developed a computer model for on-line T&D analysis which he assessed the borehole conditions based on calculating of the friction factors incrementally which starts calculating the hook load and torque bottom-up at each node with the bottom-end boundary conditions to be downhole weight on bit (DWOB) and downhole torque on bit (DTOB) and changing the friction factor until the calculated surface load matches the measured value.

Aadnoy and Andersen (2001) established analytical solutions to wellbore friction for different geometries where each section of the well profile, including straight, drop-off and build-up sections, have different equations. Further on, Aadnoy (2008) made the theory even simpler by generalize the equations for different sections of the wellbore and the movement of the pipe; either up or down.

Rae et al. (2005) used T&D simulator to firstly plan a drilling well and then use it online to calculate the hook load and torque at the surface with the model has been used for planning and then comparing the values with field surface hook load and torque data. If they agree this means that the well is drilling as it planned otherwise either a problem in the modeling or this is a warning of a problem in the wellbore.

Mason et al. (2007) pointed out different minor effects that have to be considered in the soft string models in order to have a more realistic model. One of these factors is hydrodynamic viscous force, Another is tortuosity effect. Although the preplanned well is a smooth path, the crooked profile will be resulted in reality. For this reason the model has to take this effect into account. A crooked well path shows higher T&D values. The buckling of the tubular should also be taken into account in order to have a sense of excessive drag limit which may put the string in compression such that it buckles.

Kaarstad and Aadnoy (2009) also studied experimental investigation of friction factor dependence on temperature and they observed an increase in friction coefficient with temperature and a temperature dependent friction coefficient model was presented.

The T&D modelling process is still growing but the most common models used today in the industry are (Mirhaj, 2011):

- The first model is Johancsik (1984) which is still applicable in the T&D simulators in the industry;
- Modified Texas A&M model. It was a 2-D model that have been changed into 3D in order to be applicable for side bends as well as build and drop sections.
- A new analytic fully 3D T&D model was developed by Aadnoy, Fazaeli and Hareland (2010) which incorporates many more features. It introduces one single term, dog-leg severity, for both build and drop and side bend sections.

2.2 Fundamentals of Torque and Drag:

2.2.1 Torque:

Torque is defined as the turning force that is applied to a shaft or other rotary mechanism to cause it to rotate or tend to do so, and it is measured in units of length and force. It is units depend on the unit system used, in metric system it has a unit of newton per meter (N.m). While in imperial system, it has a unit of pound force per foot (lbf.ft) (Bakke, 2012). In drilling, torque is the force or moment used to rotate the drill string, and therefore the bit, around it is axis. The torque is generated by the top drive and is used to overcome the frictional forces opposing rotation of the drill string and bit.

The top drive applies torque to the drill string and the torque stress in the string is then diminished along the string before reaching the bit where it is used to crush rock. Long deviated or horizontal sections experience greater resistance to rotation and therefore require extra torque from the top drive in order to rotate successfully and still maintain the required torque at bit. In long wells the borehole friction can become so great that it either surpasses the drill string or rig limitations and further drilling becomes impossible. Therefore, this moment applied by the top drive, surface torque, need to overcome the rotational friction against the wellbore, known as frictional torque, the viscous force between drillstring and drilling fluid, called dynamic torque, and the bit torque (Borinb, 2012).

Therefore, it is factual to say that surface torque is divided into three categories as following (Agbaji, 2009):

- The bit torque
- Torque along the wellbore
- The mechanical torque

TQ @ Surface = TQ @ Bit + TQ along the well bore + Mechanical TQ

Where:

TQ @ bit = the productive component of the torque and it depends on bit aggressiveness, WOB and bit diameter. TQ along the wellbore or frictional string torque results from the interaction between the drill string and the borehole wall. It increases with increased torsional friction losses as the drilling progresses and this is a function of friction factor, side forces, axial load, and well profile.

TQ bit = WOB * Bit Diameter * Bit Aggressiveness

Mechanical Torque is generated by cutting beds, stabilizer effects, liner centralizer and it is difficult to quantify. The frictional force, Fig.2.3 & Fig.2.4, between the borehole wall or casing and the pipe is the most important factor in ERD wells. Torque is directly proportional to the radius of the rotating pipe, the friction coefficient and the normal force exerted by the wall on the pipe. The normal force is dependent on the drill string weight including buoyancy, the well length and inclination.

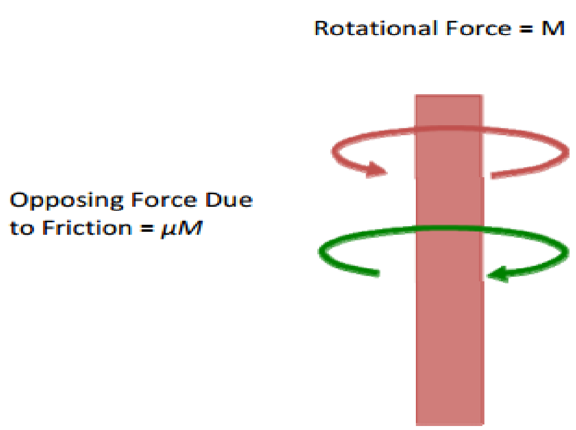


Fig.2.3: The Frictional and Surface acting Forces (Agbaji, 2009)

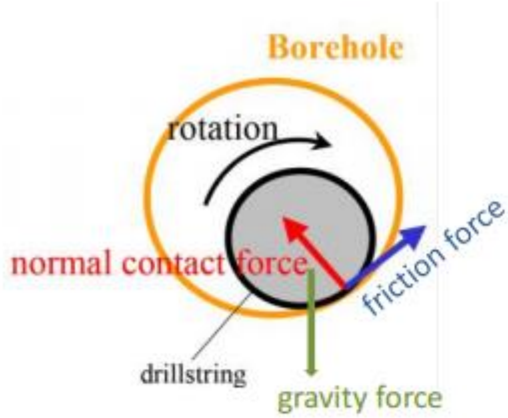
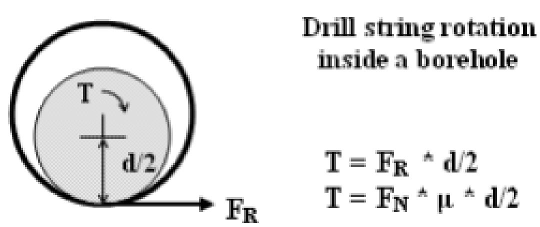


Fig.2.4: Forces on the Drillstring in Contact with the Borehole when Rotating (Menand et al., 2006).

Torque magnitude is measured by multiplying the perpendicular component of the force applied by the distance between the axis of rotation and the point where the force is applied. In drilling applications this distance would of course be the drill pipe radius. As depicted by Figure 2.5 below, torque is mathematically represented as:

Torque = **Force** x Distance



Where: d = Drill pipe OD

Fig. 2.5: Diagrammatic Representation of Torque Generating Forces (Agbaji, 2009).

The magnitude of torque is often determined by the following factors:

- Tension or compression in the drillstring
- Dog leg severity (DLS)
- Sizes of the drillstring and hole

- Weight of the string
- Directional changes of the wellbore (inclination and azimuth)
- Lubricity or friction factor

Depending on well design and drilling operation, the torque will develop in different ways along the wellbore. Analysis and projections of torque should recognize that total surface torque is comprised of many components. Clearly, separating these torque components allows more accurate definition of friction for torque projections and for prioritizing measures for torque management. With techniques available for predicting bit torque, the implications of using different bit types can be assessed (Agbaji, 2009).

2.2.2 Drag:

Drag is a resistance force to the motion of an object and it acts in the opposite direction of its axial movement. It is as a force that resists motion along a straight path. In drilling, Drag is explained as the incremental force needed to pull or lower the drillstring through the borehole, or it can also be defined as the friction forces that oppose sliding the drill string into the hole.

In drilling operations, drag results from contact between drill string components and borehole wall or casing as the string moves up or down (Fig.2.6). It is generated by friction of drill pipe against hole wall or against inside of casing. Drag will always operate in the opposite direction to that in which the drill string is being moved. It is units depend on the unit system used, in metric system it has a unit of newton (N). While in imperial system, it has a unit of pound force (lbf).

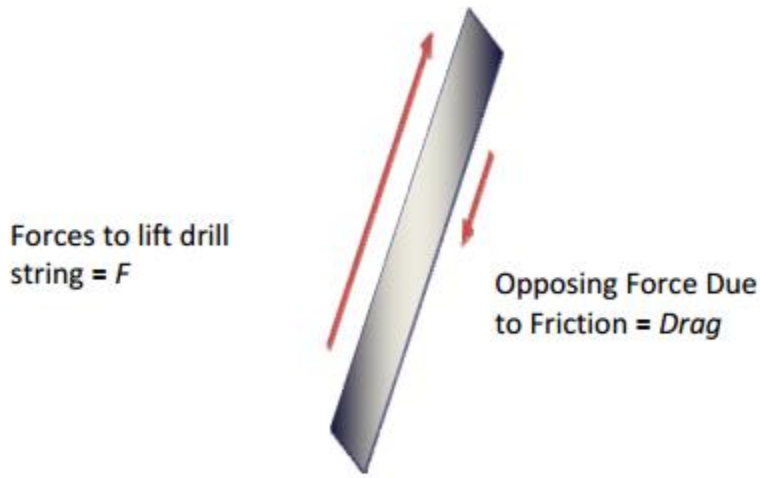


Fig.2.6: Drillstring Opposing Forces (Agbaji, 2009).

The magnitude of the drag forces, Fig.2.7, also associated with sliding friction forces or borehole friction, is depending on two factors; the normal contact force and the coefficient of friction between the contact surfaces, based on Coulomb`s friction (McCormick et al., 2011). This force is required to overcome the axial friction between the pipe and the wellbore, the hydrodynamic viscous force between the pipe string and the drilling fluid (Payne and Abbassian, 1997). A lot of factors contribute to the total friction in the well. Some of the effects are possible to model, but most of these factors are accounted for by the friction factor which is a collection of the friction contributed from the different friction sources such as local dog legs or micro tortuosity.

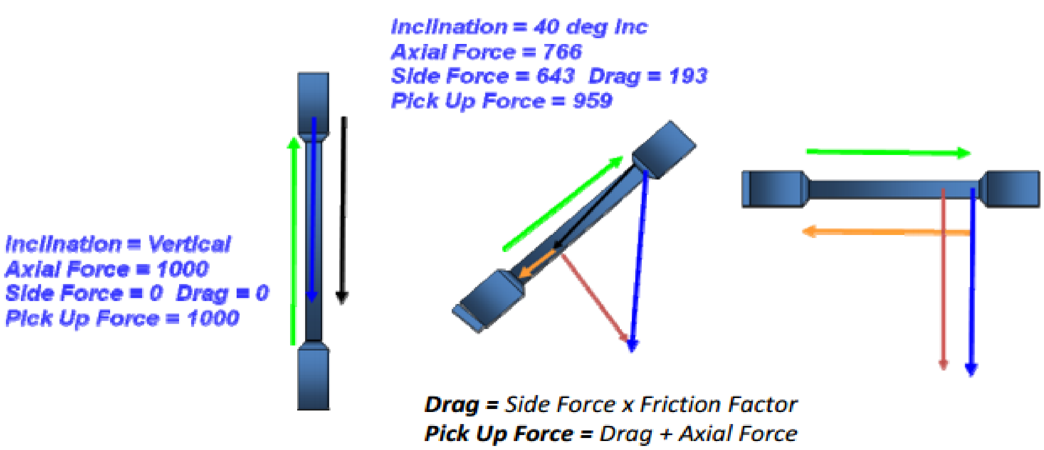


Fig.2.7: Drag and Pick up Forces (Agbaji, 2009).

Drag forces depend on many factors. Hole inclination is important as drag forces are generally not a problem in vertical strings. This is because in the deviated or horizontal wells, the string rests on the borehole or casing wall and where gravity and compressive forces push the drillstring against the borehole wall, while in vertical wells the string does not rest on the bore hole wall. Fig.2.8 illustrates drag in vertical and inclined hole.

Drag accumulates mainly when picking up, slacking off or during oriented drilling with motor. It increases with increased hole inclination and curvature due to the gravity effect and compression pushing the drill string against the low side of the bore hole and due to drillstring tension pulling up the drillstring to the high side of the hole (Borinb, 2012).

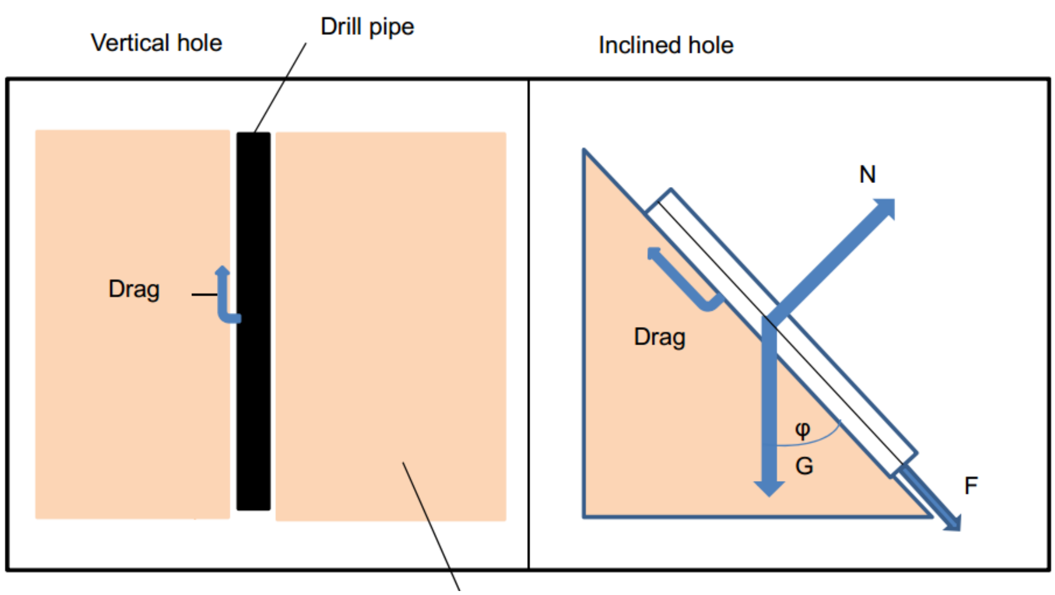


Fig.2.8: Drag in Vertical and Inclined Hole (Borinb, 2012).

2.2.3 Buckling:

Axial compression of a pipe will eventually lead to lateral deflection. A drillstring in compression will at first go into so-called sinusoidal buckling, fig.2.9, where the pipe goes from side to side in a snaky manner. If the drill pipe axial compressive load is increased further, the pipe will go into helical buckling, fig.2.10, where the drill pipe locks up in a spiraling manner against the sides of the borehole. The onset of buckling will depend of the stiffness of the string components and the outer diameter of components in relation to wellbore and casing. This is important for T&D modelling since helical buckling will cause a great increase in the side force between pipe and wellbore walls (Tveitdal, 2011).

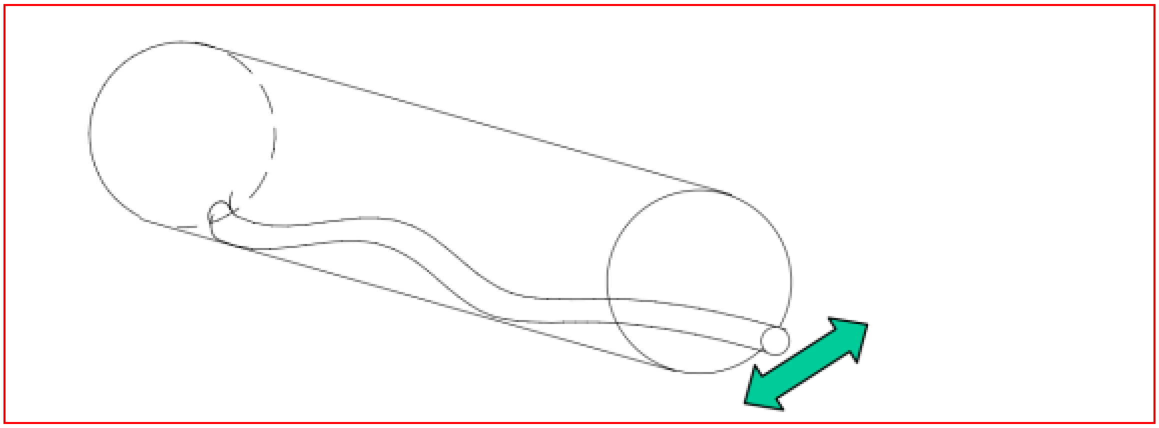


Fig.2.9: Sinusoidal Buckling (Tveitdal, 2011).

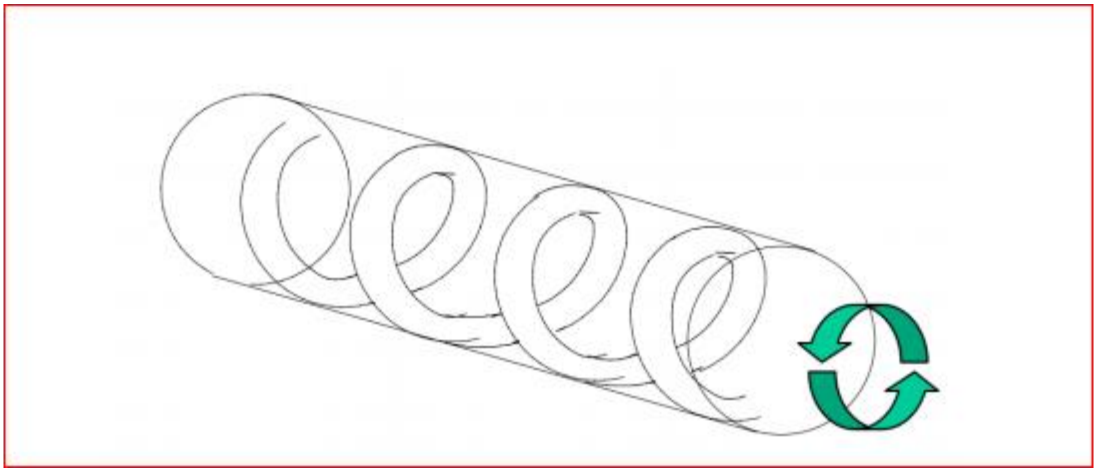


Fig.2.10: Helical Buckling (Tveitdal, 2011).

2.3 Factors affect Torque and Drag:

T&D both depend on factors like inclination, length and friction in the well and high T&D normally occur together. In general, the factors that influence T&D are listed below:

2.3.1 Wellbore Trajectory:

Torque levels in ERD wells are generally more dependent on wellbore trajectory. The angle between vertical and the wellbore trajectory is called the inclination and varies from 0 degrees in a vertical hole to more than 90 degrees for highly deviated or horizontal wells, Higher angle wells do tend to reduce overall torque levels while drilling since more of the drill string is in compression, and the tension profile in the build section is reduced.

However, higher torque values and associated problems such as accelerated casing wear and key seats are seen during backreaming operations.

There are a lot of options of trajectories available in ERD. But the selection or optimization process must consider the T&D limits results from each trajectory and how it influences the drilling process. The trajectory that makes T&D values as low as possible must be selected. Table.2.1 below shows a general list for comparison between major classes of trajectories. While the Fg.2.11 shows the well profiles.

Table.2.1: Comparison Between Major Trajectory Options (BP Extended Reach Drilling Guidelines, 1996).

Option	Advantages	Disadvantages
Multiple Build Profile: Rate of build increases with depth in several discrete steps to tangent angle, hold constant tangent angle	Very long reach, low torque/drag values, low casing wear	High tangent angle
Build and hold: Constant build rate to tangent angle, hold constant tangent angle	Simple, long reaches achievable, low tangent angle	Potentially high contact force in build (torque, casing wear)
Double build: Build-hold-build-hold trajectory, can use two different BURs in the build sections	Very long reaches possible with low contact forces in upper build	May require deep steering, High second tangent angle
Undersection: Build and hold with deep KOP	Reducing hanging weight below build section reduces contact force in build	High tangent angle, shorter reach
Inverted: Tangent angle above horizontal so the wellbore enters the reservoir from underneath	Flexibility for multiple targets, avoid gas cap	Higher axial (buckling) loads to push string uphill, deep steering required
3-D: Any of the above with significant azimuth changes	Flexibility to handle anti-collision and multiple target requirements	More curvature means more torque and drag, deep steering may be required, shorter reach

The wellbore trajectory is a critical factor in T&D, as it influences friction through a number of factors like tortuosity, hole curvature, key seating and dog leg severity.

2.3.2 Wellbore Tortuosity:

One of the major factors affecting T&D in an ERW is the tortuosity of the hole. High tortuosity results from a lack of control of toolface and deviation rate (Banks, Hogg and Thorogood, 1992). Thus, if a steerable motor is hard to orient, this will result in higher T&D, which compounds the original orientation problems.

Many authors also discussed the effect of excessive tortuousity. They stipulated that excessive tortuousity can severely limit the drillable depth and the elimination of this effect is a critical factor in successful ERD operations (Agbaji, 2009).

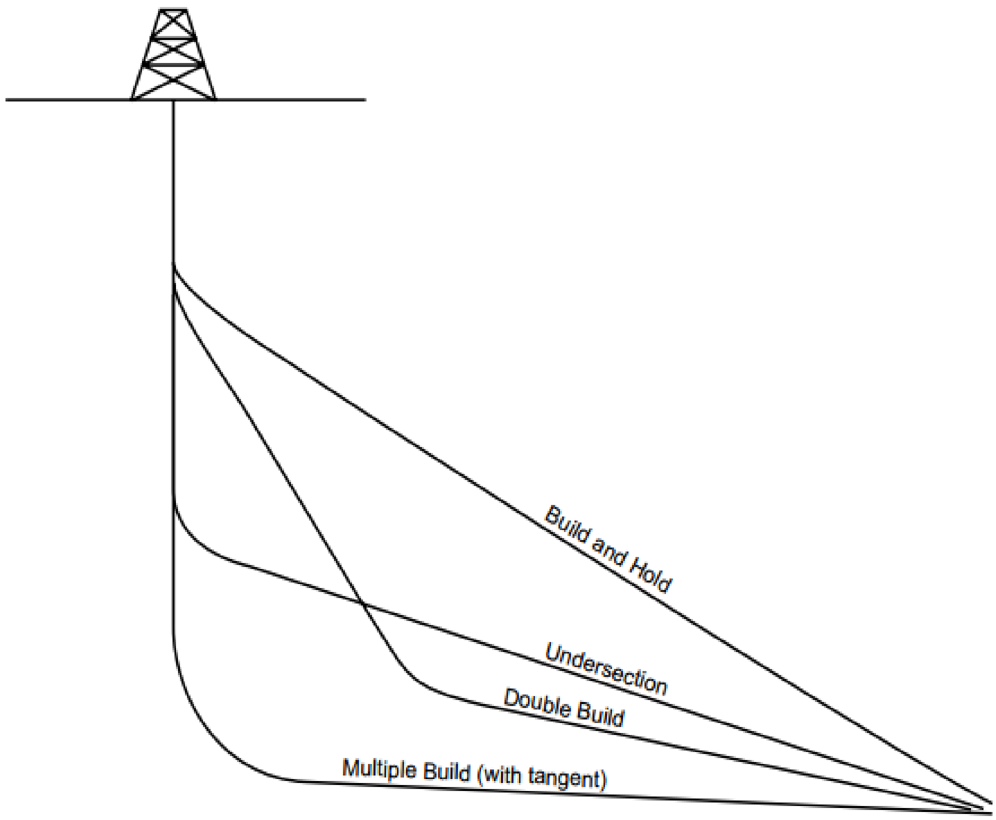


Fig.2.11: Well Profiles (BP Extended Reach Drilling Guidelines, 1996).

2.3.3 Friction Factor:

In simple physics, the coefficient of friction is a dimensionless scalar value which describes the ratio between the forces of friction between two bodies and two forces when interacting. The resulting force acts in the opposite way as from the movement of the object. The higher the friction factor the more force resists the object to move.

But, friction factor in drilling activities is much more complicated than the ordinary friction factor shown above. Here below in Fig.2.12 is a simple illustration of a simple effect of friction force.

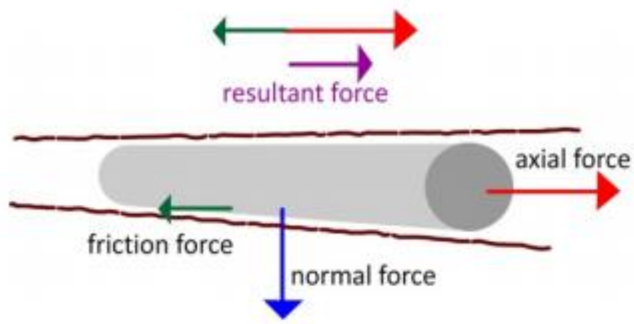


Fig.2.12: Simple Effect of Friction Force (Raksagati, 2008).

The friction factor in drilling covers the uncertainties in the wellbore so it can be exerted as a single dimensionless magnitude in calculations. There are many factors that could impact the friction factor in the drilling process beside the interaction between the drillstring and wellbore, Fig.2.13, such as:

- Cuttings bed
- DLS and well trajectory
- Mechanical equipments (BHA, stabilizer, OD tool joint)
- Mud lubricity
- Pipe stiffness effects
- Viscous drag

Modelling the above listed parameters can be a complex task because they will vary over time and depth. Because the friction factor is a function of these parameters, also the friction factor will change depending on time and depth. For instance, there will be in general, a smaller friction factor in a casing then in an openhole, (Table.2.2). The friction factor will also vary from operation to operation, such as pulling out of hole (POOH), running in hole (RIH), rotation and no rotation. This is a reason for why it is necessary to perform individual T&D analysis for different situations. Friction factor is generally given by:

$$\mu = \frac{F_F}{F_N} \longrightarrow (1)$$

Where:

F_F = Net friction force acting on the element, lbf [N]

F_N = Net normal force acting on the element, lbf [N]

μ = sliding friction coefficient between drillstring and wellbore

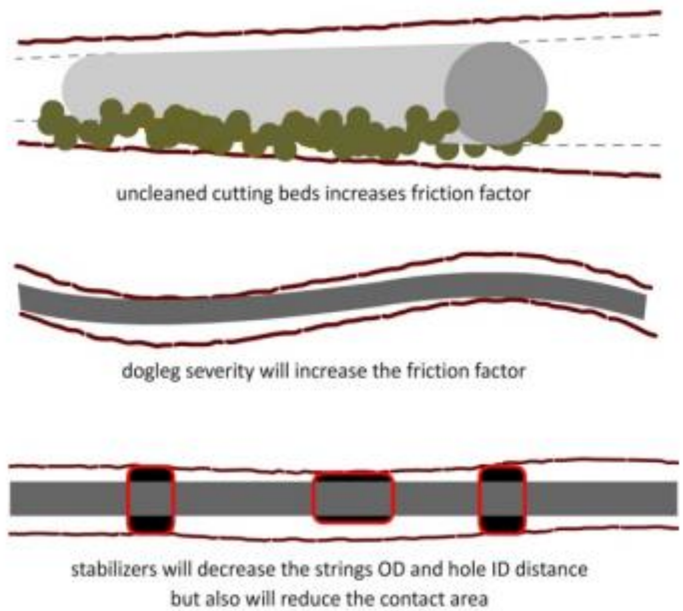


Fig.2.13: Illustration of Factors that Impact the Friction Factor (Raksagati, 2008).

Table.2.2: Ranges for Friction Factors for Different Fluid Types and Hole Conditions (Samuel, 2010).

Fluid Type	Friction Factor	
	Cased hole	Open hole
Oil-based	0.16-0.20	0.17-0.25
Water-based	0.25-0.35	0.25-0.40
Brine	0.30-0.4	0.3-0.4
Polymer-based	0.15-0.22	0.2-0.3
Synthetic-based	0.12-0.18	0.15-0.25
Foam	0.30-0.4	0.35-0.55
Air	0.35-0.55	0.40-0.60

The friction factor plays a more significant role in ERW compared to a vertical well. Fig.2.14 illustrates this, where the drillstring is forced against the side of the ERW, and in that way the friction becomes an important source of wear and energy losses in the tubular system. The drillstring is in general placed centrally in the borehole in a vertical hole, leading to negligible contact between the drillstring and the borehole wall, and consequently zero T&D.

The middle sketch in Fig.2.14 shows that during a build section the drillstring is pressed against the top side of the borehole wall and is in tension or compression, leading to varying degree of T&D forces. The right picture in Fig.2.14 presents a tangential section of the hole where the entire drillstring is in contact with the low side of the borehole wall, and can be in some tension or compression (Aadnoy et al. 2010; Xie et al. 2012; Bennetzen et al. 2010).

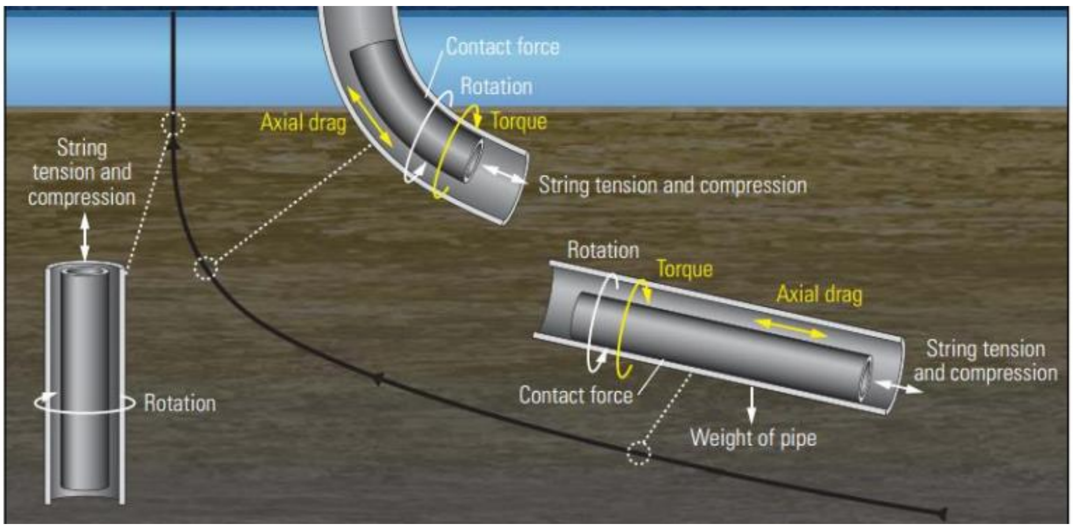


Fig.2.14: Side Forces on the String in Wellbore Orientations (Bennetzen et al. 2010).

Friction factor is commonly divided into Static and kinetic friction. Static friction occurs when there is no movement between the two bodies. Static friction is often larger than kinetic friction. Kinetic friction is the friction between two contacting bodies in movement relative to each other Both static and kinetic friction factors are important in drilling, but for T&D simulations the kinetic friction is modeled (Mason and Chen, 2007).

2.3.4 Weight:

The weight of the drill pipe is extremely important for T&D. The weight depends on the material density of the pipe and pipe wall thickness. To calculate mass of a pipe the equation below is used:

$$M = \rho_{pipe} * V \longrightarrow (2)$$

Where:

$M =$ Mass of pipe

$\rho =$ Density of pipe

$V =$ Volume of pipe material

Nominal weight in lb/ft is often used in tables and is calculated from this equation:

$$m = \rho\pi(r_o - r_i) \longrightarrow (3)$$

Weight including tool joints is calculated from the following equation:

$$M = \rho_{pipe}\pi(r_o^2 - r_i^2)(l_{pipe} - l_{tj}) + M_M + M_F \longrightarrow (4)$$

Where:

$r_o =$ Pipe outer radius

$r_i =$ Pipe inner radius

$l_{pipe} =$ length of pipe

$l_{tj} =$ length of tool joint

$M_M =$ Mass of male tool joint

$M_F =$ Mass of female tool joint

After the pipe weight is calculated. Then, it is used to calculate the borehole normal force on the pipe from the equation below:

$$F_N = M\, g \sin\alpha \longrightarrow (5)$$

Where:

$g =$ gravity constant

$\alpha =$ borehole inclination

The normal force is then used to calculate friction force by multiplying it with the friction factor from the equation below:

$$F_F = F_N * \mu \longrightarrow (6)$$

The friction force is the major constituent of T&D. Any reduction of friction force will therefore give a direct reduction in T&D forces. Materials like aluminum and titanium have lower density than steel, and the normal force will be smaller for these materials than the alternative steel equivalent (Borinb, 2012).

2.3.5 Buoyancy:

For drill pipes, the buoyancy equals the weight of the mud that the drill pipe displaces. The submerged weight of a wellbore tubular can be obtained by multiplying the weight in air with a buoyancy factor:

$$\beta = \frac{\text{Suspended weight in mud}}{\text{Weight in air}} \longrightarrow (7)$$

Where:

$\beta = \text{buoyancy factor}$

And it is given by the following equation:

$$\beta = 1 - \frac{\rho_{\text{fluid}}}{\rho_{\text{pipe}}} \longrightarrow (8)$$

$\rho_{\text{fluid}} = \text{density of fluid the pipe is submerged in}$

The above equation is only valid if the mud inside and outside the drill pipe has the same density. This is not always the case, and for operations that involve different density fluid inside and outside the wellbore tubular, such as cementing operations and displacement of mud, the following formula must be used:

$$\beta = 1 - \frac{\rho_{\text{mo}} r^2 - \rho_{\text{mi}} r^2}{\rho_{\text{pipe}}(r_o^2 - r_i^2)} \longrightarrow (9)$$

Where:

$\rho_{\text{mo}} = \text{density of mud outside the pipe}$

$\rho_{\text{mi}} = \text{density of mud inside the pipe}$

Using a mud with high density will give more buoyancy than using a less dense mud, and therefore influence T&D simulations. The opposite is true for the drillstring, using a less dense material will reduce T&D (Borinb, 2012).

2.4 Torque and Drag Reduction Methods:

A variety of methods are available to reduce T&D, the application of such methods can be essential for making sure the T&D can be reached before reaching the torque limit of the rig or drillstring. These methods are:

2.4.1 Wellpath:

Tortuosity reduction reduces significantly the T&D while drilling, the use of rotary steerable systems (RSS) are recommended to make the smoothest wellbore. As even small adjustments to the target may reduce the torque. Reducing the DLS in buildup, drop off and bends can significantly reduce T&D especially at the top of the well where tension forces are greatest.

2.4.2 Rotary Steerable Systems:

A hole drilled with a mud motor with a bent sub has generally greater tortuosity than with a RSS, this is due to the steering principle of such tools. Directional drillers obtain the desired DLS by switching from rotary drilling to sliding drilling as many times as needed. Rotary drilling with motor creates smaller hole than sliding. Drilling with motor creates a larger hole than a RSS will do. While sliding, a high DLS is achieved to correct for the direction achieved by rotary drilling, this is a due to a combination of gravity and centralizer placement. This continued alteration is the reason why motors create much more tortuosity than a RSS. Adding a mud motor to an RSS will increase ROP, while RPM at surface can be reduced to minimum and thus reduce the torque. Using RSS with integrated mud motor will reduce surface torque as compared to a conventional RSS (Maehs et al. 2010).

2.4.3 Bit Selection:

Bit selection is normally based on ROP but another factor is important as well. The gauge length can significantly affect the propagation of a cyclic hole. A short gauge bit is more aggressive and creates more caliper variations and what is called micro tortuosity. While a long gauge bit tends to create less caliper variations and a smoother hole. This micro tortuosity is not seen by MWD directional sensors, and will add extra T&D. This can be seen as measured T&D trends deviate from simulated trends (Gaynor, 2002).

2.4.4 Mud System:

The easiest way to reduce T&D is to use oil based mud (OBM) or synthetic based mud (SBM) instead of water based mud (WBM). It is also possible to add lubricants, even to WBM.

2.4.5 Mechanical Reduction Techniques:

Mechanical friction reducing subs have been tried and proven successful in reducing friction. They have been deployed as a contingency in wells where T&D forces became higher than expected, and halted drilling before reaching planned total depth. The subs are typically placed one per stand in the sections of the well that sees the highest side force. It should be noted that these tools also reduce the casing wear (Long, et al., 2009).

2.5 Torque and Drag Modelling:

The ability to confidently predict that you can reach a reservoir target is probably the biggest problem when drilling an ERD well. This makes the accurate prediction of T&D very essential. T&D forces play important role when planning and operating an ERD well (Agbaji, 2009).

T&D modelling software has been used extensively since the 1990's. Especially in complex and long ERD wells, where the loads are near the limits of equipment material. It is essential to apply a T&D model to obtain a successful well. Models are applied to analyze friction, in terms of a friction factor, to estimate how it affects hook load and torque. To get an accurate model, it is therefore important and challenging to find appropriate friction factors for different situations (K&M Technology Group, 2003).

T&D models have proven to be useful in all three stages of an ERD well: planning, drilling and post-analysis. During planning phase the models are used to optimize the trajectory design to minimize the T&D and contact forces between drillstring and borehole wall. Used together with monitoring of hole conditions during drilling, T&D models are particularly useful in diagnosing hole problems. In post-analysis the models help to determine true causes of hole problems that previously were unexplained or attributed to other factors.

The model has to be of high quality, and also be easy to apply. A reliable and accurate model has to model realistic forces, contact loads and bending moment, and at the same time be as user friendly as possible.

In the past, several attempts to develop a good model have been done, and still some confusion remains over the validity of the models used to characterize the well operations. First out was the well-known two dimensional (2D) model to Johansick, which is still commonly applied in the industry today. Another relevant model is an analytical three dimensional (3D) model developed by Aadnoy et al. The 3D model can be either applied as a fully 3D model, when both inclination and azimuth are changed, or be applied more simplified as a 2D model if the azimuth is negligible in the well path. The 3D model is relatively new and less familiar to the industry, (Frafjord, 2013).

In this project computing T&D have been done using landmark software. But before proceeding to the next chapters, understanding the basics physics equations is necessary to know the basics.

2.5.1 Basics of Torque and Drag Modelling:

The T&D model is based on a simple mathematical model. This model assumes that the load on the drillstring is only dependent to the effects of gravity and frictional drag mentioned before as friction factor. The force that indicates the magnitude of interaction between the string and the hole is the normal force. Normal force in this model is contributed by (Raksagati, 2008):

- effects of gravity
- effects of compression and tension in the welbore cuvatures

Fig.2.15 is a simple free body diagram of the string with the wellbore.

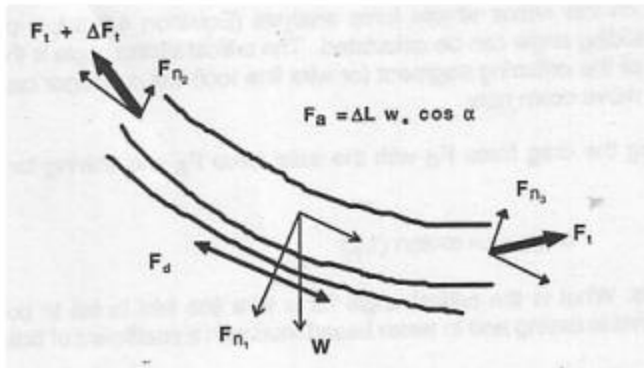


Fig.2.15: Drillstring Free Body Diagram (Raksagati, 2008).

With reference to the above free body diagram, researchers derivate it into equations that could calculate T&D. These equations are listed below as following:

$$F_N = [(F_t \Delta\theta \sin\alpha)^2 + (F_t \Delta\alpha + W_e \sin\alpha)^2]^{0.5} \longrightarrow (10)$$

$$\Delta F_t = W_e \cos\alpha \pm \mu F_N \longrightarrow (11)$$

In the above equation the plus sign is used in case of tension, while the minus sign is used in case of compression.

$$\Delta T = \mu F_N r \longrightarrow (12)$$

$$F_t = F_t + \Delta F_t \longrightarrow (13)$$

$$T = T + \Delta T \longrightarrow (14)$$

Where:

F_N = Net normal force acting on the element, lbf [N]

F_t = Axial tension force acting at the lower end of the element, lbf [N]

ΔF_t = Increase in tension over the length of element, lbf [N]

T = Torsion at the lower end of the element, ft − lbf [Nm]

ΔT = Increase in tension over the length of the element, ft − lbf [Nm]

μ = sliding friction coefficient between drillstring and wellbore

r = characteristic radius of drillstring element, ft [m]

α = Average wellbore inclination, degrees [rad]

W_e = buoyed weight of drillstring elemen, lbf [N]

θ = Azimuth angle at lower end of drillstring element, degrees [rad]

$\Delta\theta$ = increase in azimuth angle over length of element, degrees[rad]

$\propto$= inclination angle at lower end of drillstring element, degrees [rad]

$\Delta\alpha$ = increase in inclination angle over length of element, degrees [rad]

2.5.2 Description of Torque and Drag Modelling process:

The calculation of T&D forces can be divided into two categories: One case is when the friction coefficient is given and the other is when the friction coefficient is not given.

2.5.2.1 Calculation Procedure when Friction Coefficient is given:

This calculation procedure is made directly. But the drillstring description and wellbore survey data are required. Once the drillstring description, survey data, and friction coefficient are specified, the calculation starts at the bottom of the drillstring and proceeds stepwise upward. Each short element of the drillstring contributes small increments of axial and torsional load to running totals in the control program. Calculation of these load increments is the heart of the whole calculation. Calculation of the normal force is the first step in calculating the load increments for an element of the drillstring. The net normal force, F_N, is the negative vector sum of normal components from the weight, W, and from the two tension forces, F_t and $F_t + \Delta F_t$. Even though the axis of the element is assumed to be an arc of a circle, this circle is not usually vertical and therefore the net normal force is not usually in the vertical plane. Fortunately, the friction calculation requires only the magnitude of the normal force, not its direction.

The magnitude of the normal force, F_N, is calculated from eq. (10). Once the value of F_N is determined, this leads directly to eq. (11) to calculate tension increment , ΔF_t, and then torsion increment, ΔT, from eq. (12) (Johancsik, Friesen and Dawson, 1994).

2.5.2.2 Calculation Procedure when Friction Coefficient is not given:

Also called the reverse calculations. The friction coefficient is determined from given T&D data, field data, and it is done by assuming a friction coefficient and iterating to match the given data. In this case also the drillstring description and wellbore survey data are required.

The above two calculation procedures nowadays is easier when computer software simulation take place (Johancsik, Friesen and Dawson, 1994).

2.5.3 Benefits of Torque and Drag Modelling:

T&D analysis have an essential part in drilling design. T&D modelling although often uses data from other field and with many uncertainties is nearly always conducted, this is because there are benefits that can be obtained from this analysis, such as (Tveitdal, 2011):

- Trajectory design to minimize T&D forces
- Assist in well planning and to predict and prevent drilling problems
- To determine the drilliability of the well and improve the design
- To prepare rotating system rig capacity, the obtained surface torque data generated in the model could be a useful reference in determining it
- To prevent buckling limitation when drilling of well, if the axial force, tension, or compression shown in the model exceeds the critical buckling force then, the drilling plan must be readjusted
- To prepare the rig capacity when maximum hookload from model is known and plus a certain of safety factor and margin overpull
- To know the magnitude of torque on bit
- To prepare the block weight and string configuration needed.
- An aid in determining if a changes to the mud is necessary
- Monitoring hole cleaning in real time
- Determining if drill string torque limits may be exceeded

Chapter Three

Methodology

As mentioned previously, T&D modelling in this project have been done using Landmark software. Landmark software has basically two components; Compass and Wellplan. In this project T&D modelling will be done using Wellplan but there are necessary data need to be inputted into the Compass in order to get the well geometry. Before proceeding to the modelling process it is necessary to briefly explain the landmark software and it is components.

3.1 Landmark:

3.1.1 Compass:

Compass is a directional well planning software developed by Halliburton. It is used for path planning, survey data management, and anti-collision analysis. The software is deployed on Landmark's Engineer's Data Model (EDM) enabling data consistency and reduced planning cycle times by sharing common data compass has three core functions; planning to design the shape of proposed well paths, survey to calculate as drilled wellpath position, and anticollosion to calculate distance between wellpaths (Landmark Compass user manual, 1996).

3.1.2 Wellplan:

Wellplan is a component of Landmark software developed by Halliburton. Wellplan software is able to solve number of technical challenges such as ERD, slim hole drilling, deep water drilling, and environmentally sensitive drilling areas. Wellplan software can be used at the rig site and in the office to provide integration between engineering functions. It is used during the design and operational phases for drilling and well completion. This software allows the user to identify potential problems during the drilling and completion process in terms of wellbore design. Integrated technologies enables the user to study and evaluate BHA, torque and drag, stuck pipe, cementing, hydraulics and well kick scenarios. For this particular project the main focus will be on the T&D module.

Wellplan T&D Analysis software provides knowledge of anticipated loads for drilling and casing operations. It can be applied to diagnose the measured weights and torques that can be expected during tripping in, tripping out, rotating on bottom, rotating off bottom, sliding drilling, backreaming. Based on the simulation results, engineers are able to determine if the selected rig has good enough mechanical specifications to handle the well design requirements, also if the well can be drilled, or to evaluate what is occurring while drilling a well.

T&D analysis (TDA) uses the principle of force equilibrium and is based on Dawson's cable model, or soft string model as it is commonly known. The work string is treated as an extendible cable with zero bending stiffness. For contact force analysis the string may be imagined as lying against the side of the wellbore although for calculation simplicity the centre line of the work string is assumed to follow the centre line of the wellbore. Friction is assumed to act in one direction, this being defined by the type of analysis; running in, pulling out, and rotating. Wellplan T&D model does not include wellbore cleaning aspects and assumes that all the cuttings are removed (Landmark Wellplan user manual, 2000).

In this project, T&D modelling process will be done in the following conditions or operations:

- Tripping in
- Tripping out
- Rotating off bottom
- Rotating off bottom.

But before proceeding to this step, the next paragraphs will give a brief review of such operations.

3.2 Relevant Activities During Drilling of a Well:

Activities which can be performed during the drilling of a well and recognized from real time data include the following:

- Drilling with no, or neglected, movements in axial direction.

- Reaming
- Tripping in without rotation, RIH
- Tripping out without rotation, POOH
- Pick up/rotate/slack off, PRS, test

3.2.1 Drilling:

Drilling is to enlarge the borehole by rotating the string and bit on bottom of the borehole. The velocity in axial direction or rate of penetration, ROP, is much smaller than the rotational speed or revolution per minute, RPM, and the situation can therefore be seen as a case with drillstring rotation without axial movement.

3.2.2 Reaming:

Reaming operation is performed during drilling of a well by moving the pipe while maintaining or modify drilling parameters, such as string rotation and circulation. Reaming can be done while lowering the string or pulling the string, but is different from tripping because in tripping, rotation and circulation are stopped, meaning zero torque and RPM. Reaming is performed for instance to clean the hole, or to make the drilled hole smoothly larger to an exact hole size in plastic formations that slowly creep and reduce the wellbore diameter over time (Frafjord, 2013).

3.2.3 Tripping Operations:

Tripping is moving the pipe without rotation and circulation, and is often measured while the pipe is pulled out of hole and before making a connection. Measurements from operation without rotation are helpful to apply to analyze the downhole situation, because just here the full friction, which is acting in the axial movement and affecting the hook load, is on its maximum.

One way of getting an indication on the resistance, or friction, when moving the pipe in the borehole, is by directly study the hook load during tripping operations and apply the theory in the T&D model. Measured hook load at the surface can indicate the friction, which is force, in terms of weight, needed to move the pipe up or down, by studying the deviation in tension when going in and out with the string (Kucs, et al., 2008).

3.2.4 Pickup/Rotate/Slack off test:

Pickup/rotate/slack off test, PRS test, is an operation that can be identified from the real time data. PRS tests are done to make T&D analysis more effective by maintaining a working understanding of the friction factor and by systematically gather drilling mechanics data.The test is common to do at the casing shoe whenever tripping in or out after drilling every stand. The procedure for the test is to record hook load and torque when picking up the drillstring, rotating the stationary string and slacking off, and it is performed when pumping and then when not pumping (Rae, et al., 2005).

As mentioned early, the interest herein this project is mainly about T&D modelling during tripping in, tripping out, and drilling.

3.3 Trajectory of the Tested Wells:

3.3.1 ABMO-1 Horizontal Well Trajectory:

The well ABMO-1 is a horizontal well located in field X, block 2b. The well start vertically with a kick off point of approximately 3050ft MD and a first build section from kick off point to 3386.5ft MD. From this depth the second build section starts to build the angle from 8.2º to 90º at 6783ft MD. Then a horizontal section starts from 6783ft MD to TD i.e. 7767ft MD.Fig.4.1shows the geometry of ABMO-1 well and fig.4.2 shows the vertical section. T&D analysis results can be seen in fig.4.7 through fig.4.14 in chapter four.

3.3.2 ABMO-1 ERD Well Trajectory:

ABMO-1 horizontal well will be extended in the horizontal section by about 3280ft. Since the ratio between MD and TVD become greater than 2, the extended ABMO-1 horizontal well is now considered an ERD well and will be referred to as ABMO-1 ERD well in the next chapters of this project.

Then T&D analysis will be performed on ABMO-1 ERD well to analyze the T&D for this well and to know how long the horizontal section of this well could be extended, drillability of the well, without significant problems. This well profile, as fig.4.15 shows, is a very good example for T&D modelling as all different sections of well geometry exist including straight, inclined, curved and horizontal sections.

It is necessary to say that the subsurface geology of the field X permits creation of a horizontal section for more than the assumed 3280ft. Also the target i.e. Bentiu can be considered as a horizontally extended formation, as can be seen in fig.3.1, which in turn permits a horizontal extension more than the assumed 3280ft.

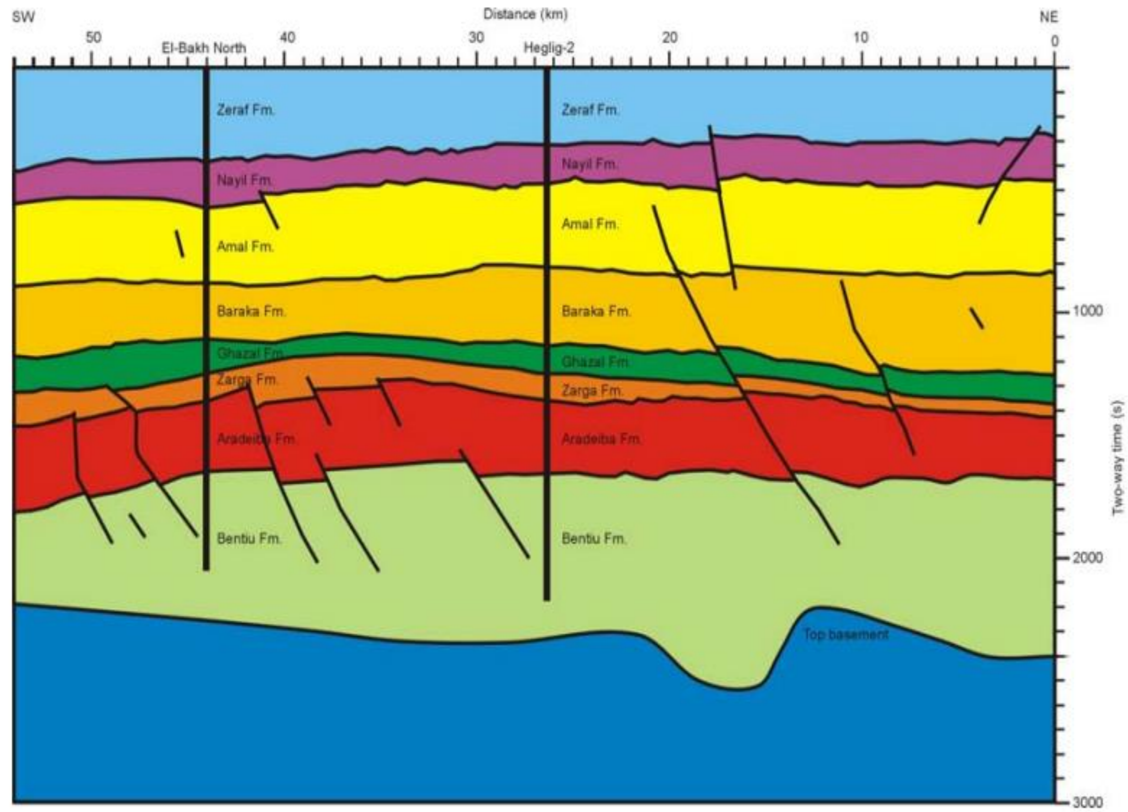


Fig.3.1: Cross Section Constructed from the Interpretation of Seismic Data (Ibrahim, 2003).

It should be noted that the ABMO-1 horizontal well is assumed to be completed to an ERD well using double build profile, catenary profile, which has an advantage of a relatively low T&D values and low casing wear compared to other profiles such as build and hold trajectory.Fig.4.15 shows the geometry of ABMO-1 ERD well, also the DLS for ABMO-1 ERD well is not too high as can be seen in fig.4.19.

3.4 Torque and Drag Modelling Methodology:

3.4.1 Analysis of existing Data:

1- The analysis process involves reviewing of the available well and field data to understand and collect the data needed for the modelling process such as:

- Field and wells surface and subsurface data. In addition to the target location data.
- BHA and drillstring data for the well.
- Well trajectory
- Mud properties
- Actual field T&D data

2- Loading all the available data into the landmark software in order to get the geometry of the wells and simulate T&D.

2.4.2 Input Data into Compass :

The need for Compass in this project is to generate the well trajectory or profile for both; the ABMO-1horizontal well and ABMO-1ERD well. Before inputting the survey data, to get the well geometry, there is some basic data need to be inputted such as: new company, new field, new site, new well, and new wellpath. The fig.3.3, fig.3.4, fig.3.5, fig.3.6, fig.3.7, illustrates the data inputted to each section respectively. Then, the survey data will be entered from the well plan report. It should be noted that the survey data in this project can be found in appendix A.

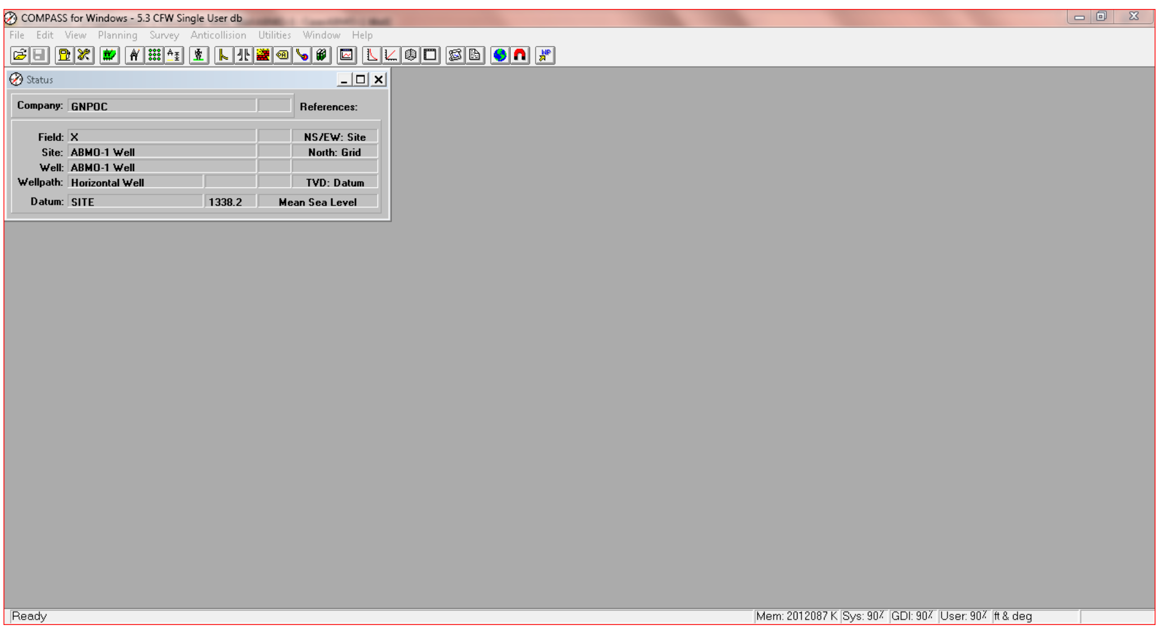


Fig.3.2: Compass User Interface (Compass).

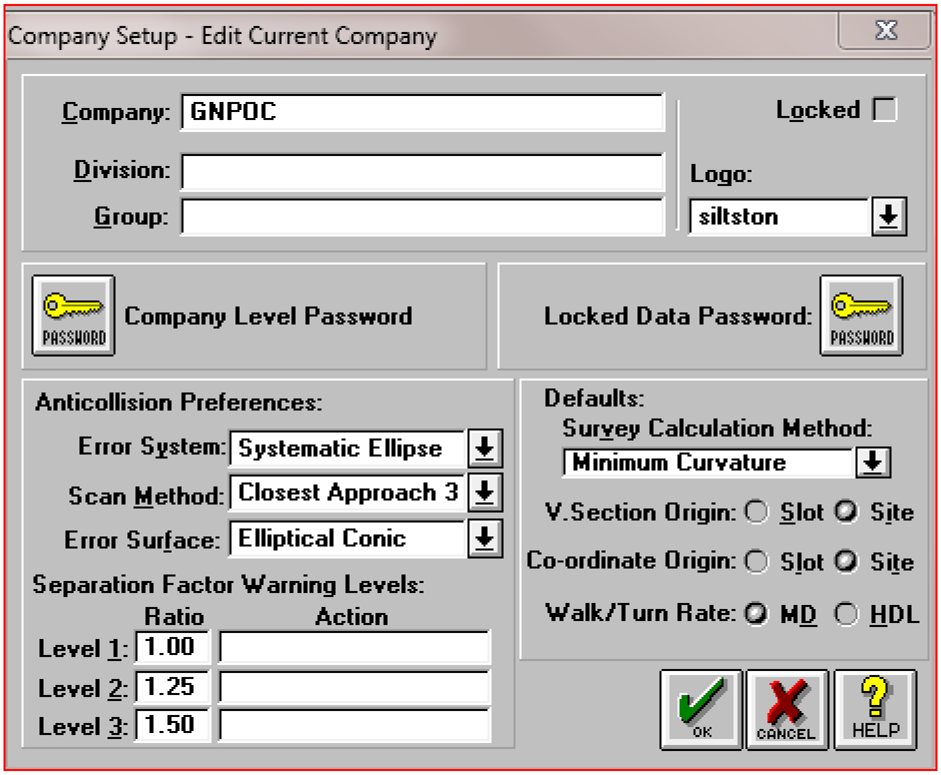


Fig.3.3: Company Setup (Compass).

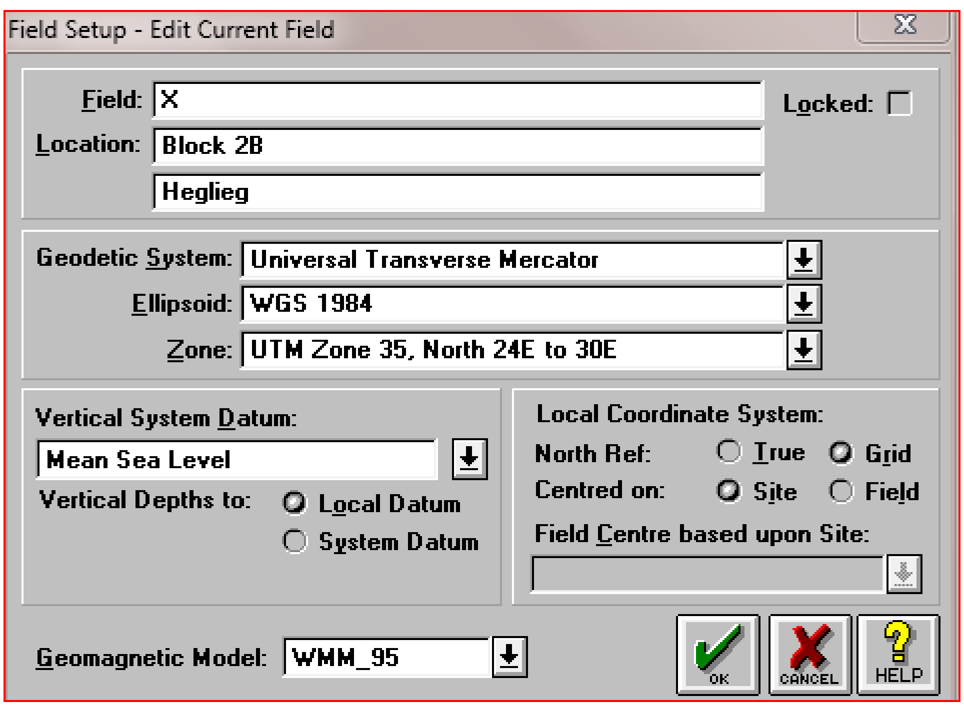


Fig.3.4: Field Setup (Compass).

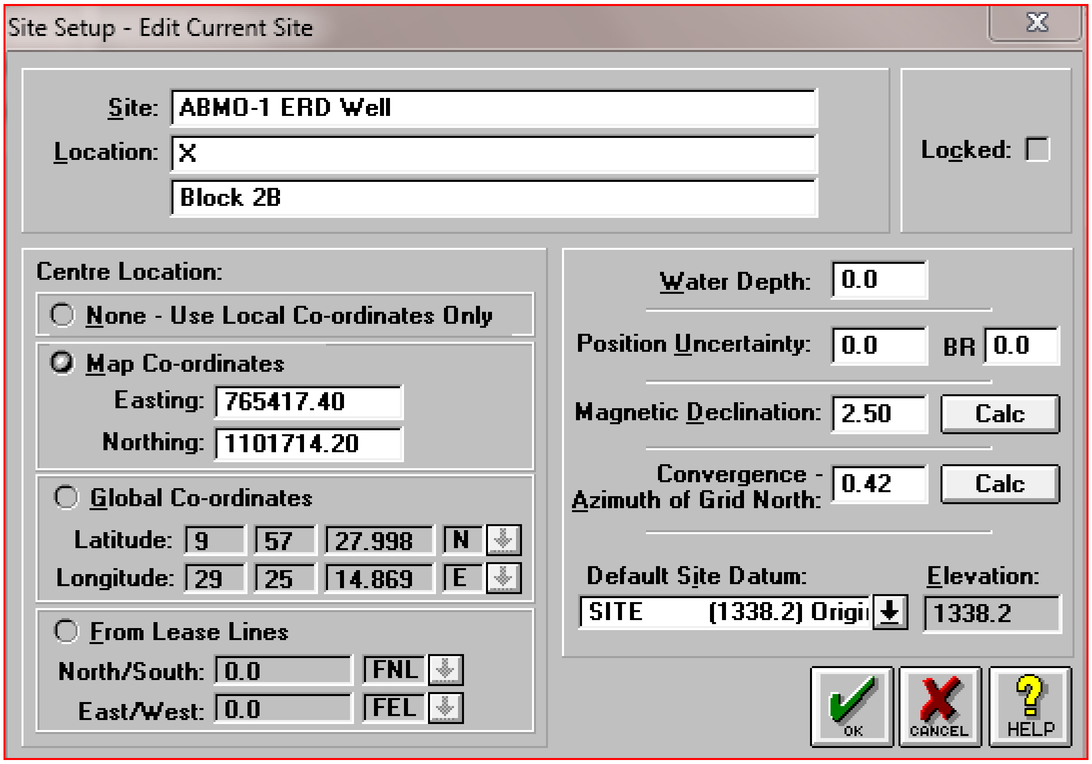


Fig.3.5: Site Setup (Compass).

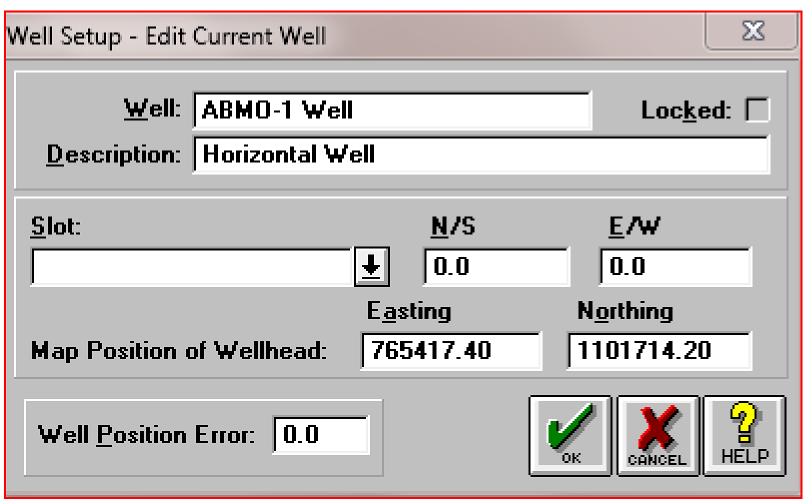


Fig.3.6: Well Setup (Compass).

Fig.3.7: Wellpath Setup (Compass).

2.3.5 Input Data into Wellplan:

As mentioned before, T&D modeling in this project will be done using Wellplan. There is T&D module and cases and parameters that need to be inputted. Here is a brief explanation of what data has been inputted and what data is assumed.

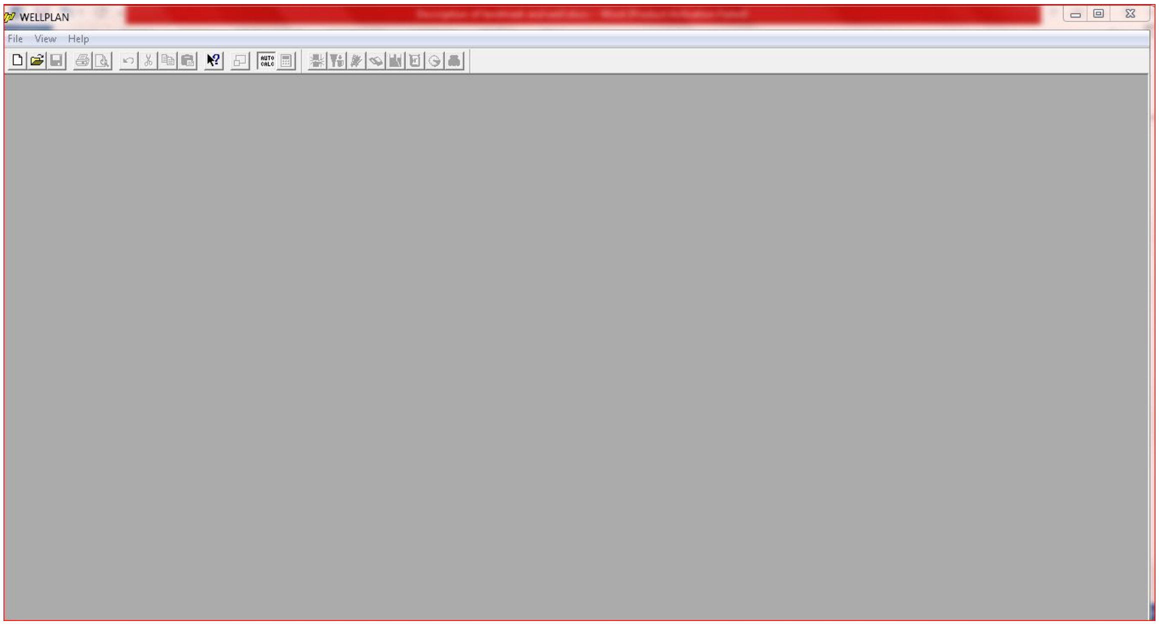


Fig.3.8: Wellplan User Interface (Wellplan).

2.3.5.1 General:

In this section inputting the general data from the well such as Origin N, E, Azimuth, well depth MD and reference point is inputted.

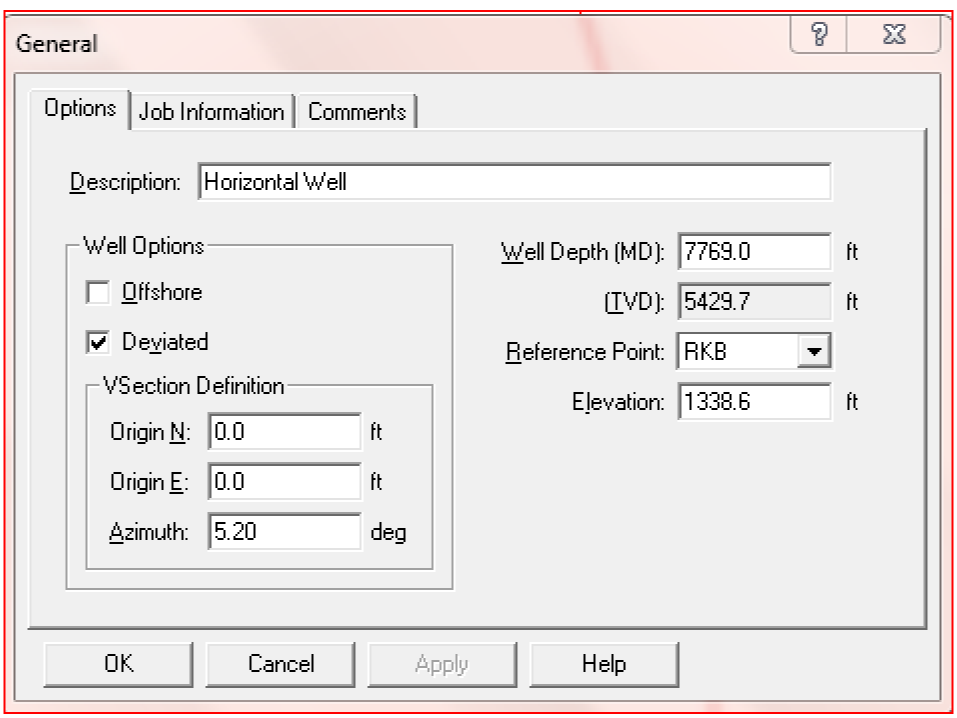


Fig.3.9: ABMO-1 Horizontal Well General Data (Wellplan).

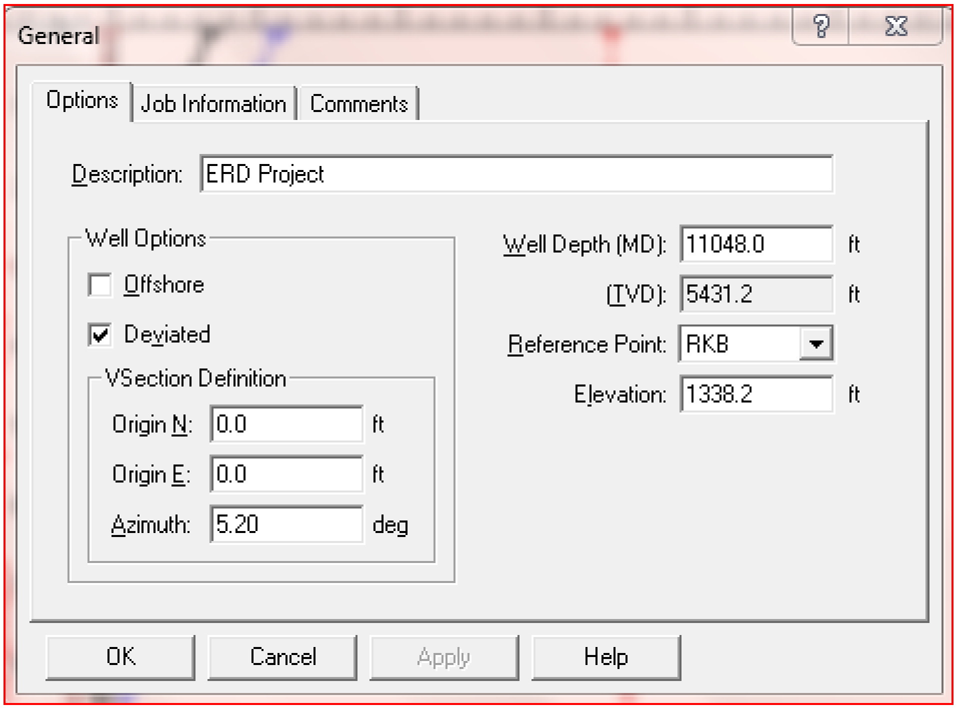


Fig.3.10: ABMO-1 ERD Well General Data (Wellplan).

2.3.5.2 Wellbore Editor:

Wellbore editor enables the user to input the wellbore information for casing and open hole such as Length, internal diameter (ID), and friction factor. The friction factor is assumed or could be matched later with the actual data. It should be noted that in this project the friction factor is matched with the available actual T&D data.

Wellbore Editor

Well Depth (MD): 7769.0 ft

	Section Type	Depth (ft)	Length (ft)	ID (in)	Drift (in)	Effective Hole Diameter (in)	Friction Factor	Volume Excess (%)	Catalog Summary
1	Casing	98.4	98.43	20.000	18.936	24.000			CAS 20 in, 94.00 ppf, K55, BTC
2	Casing	2837.9	2739.50	12.750	12.259	17.500			CAS 13 3/8 in, 68.00 ppf, K55, BTC
3	Casing	6756.8	3918.87	9.625	8.750	12.750			CAS 9 5/8 in, 40.00 ppf, K55, BTC
4	Open Hole	7769.0	1012.20	8.500		8.500		0.00	
5									

Fig.3.11: ABMO-1 Horizontal Wellbore Editor (Wellplan).

Wellbore Editor

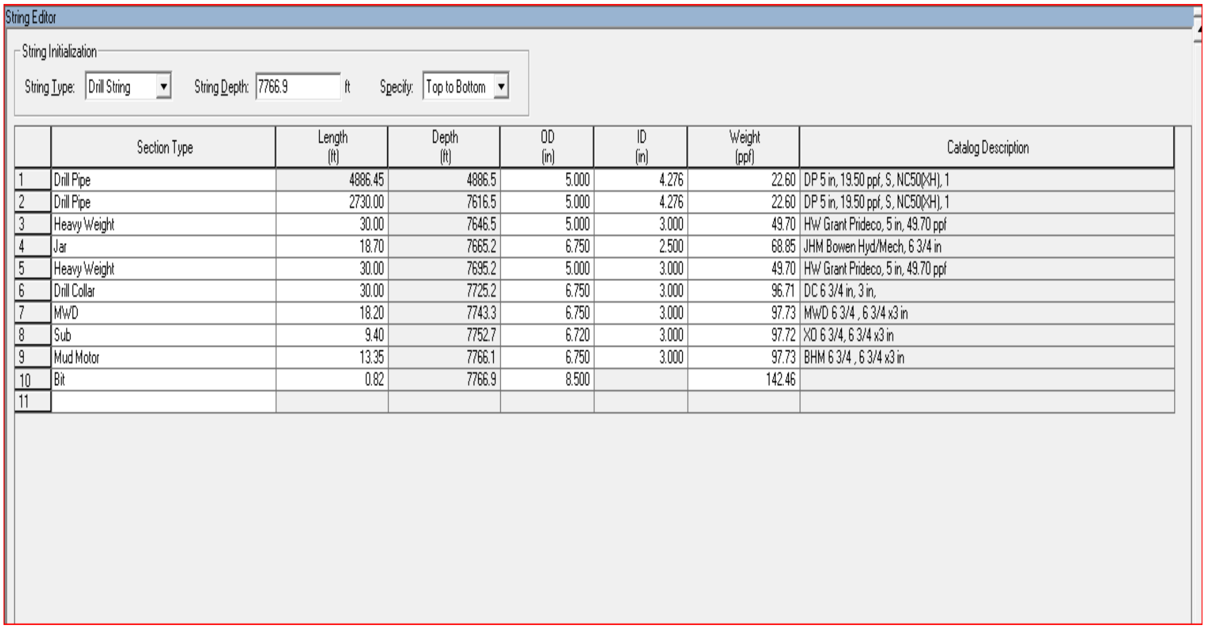
Well Depth (MD): 11048.0 ft

	Section Type	Depth (ft)	Length (ft)	ID (in)	Drift (in)	Effective Hole Diameter (in)	Friction Factor	Volume Excess (%)	Catalog Summary
1	Casing	98.4	98.40	20.000	18.936	24.000	0.26		CAS 20 in, 94.00 ppf, K55, BTC
2	Casing	2837.2	2738.80	13.375	12.259	17.500	0.26		CAS 13 3/8 in, 68.00 ppf, K55, BTC
3	Casing	6756.8	3919.60	9.625	8.750	12.250	0.26		CAS 9 5/8 in, 40.00 ppf, K55, BTC
4	Open Hole	11048.0	4291.20	8.500		8.500	0.32	0.00	
5									

Fig.3.12: ABMO-1 ERD Wellbore Editor (Wellplan).

2.3.5.3 String Editor:

String and BHA data can be inputted in the string editor. It includes the outer diameter, yield strength, torsional strength, weight, etc.

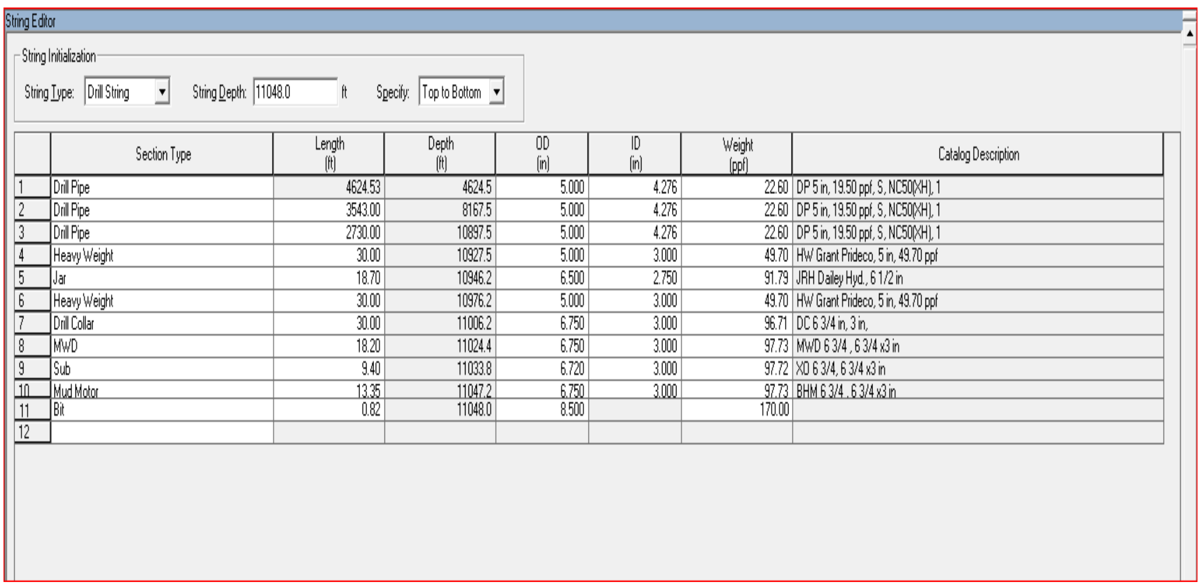

String Editor

String Initialization

String Type: Drill String | String Depth: 7766.9 ft | Specify: Top to Bottom

	Section Type	Length (ft)	Depth (ft)	OD (in)	ID (in)	Weight (ppf)	Catalog Description
1	Drill Pipe	4886.45	4886.5	5.000	4.276	22.60	DP 5 in, 19.50 ppf, S, NC50(XH), 1
2	Drill Pipe	2730.00	7616.5	5.000	4.276	22.60	DP 5 in, 19.50 ppf, S, NC50(XH), 1
3	Heavy Weight	30.00	7646.5	5.000	3.000	49.70	HW Grant Prideco, 5 in, 49.70 ppf
4	Jar	18.70	7665.2	6.750	2.500	68.85	JHM Bowen Hyd/Mech, 6 3/4 in
5	Heavy Weight	30.00	7695.2	5.000	3.000	49.70	HW Grant Prideco, 5 in, 49.70 ppf
6	Drill Collar	30.00	7725.2	6.750	3.000	96.71	DC 6 3/4 in, 3 in,
7	MWD	18.20	7743.3	6.750	3.000	97.73	MWD 6 3/4 , 6 3/4 x3 in
8	Sub	9.40	7752.7	6.720	3.000	97.72	XO 6 3/4, 6 3/4 x3 in
9	Mud Motor	13.35	7766.1	6.750	3.000	97.73	BHM 6 3/4 , 6 3/4 x3 in
10	Bit	0.82	7766.9	8.500		142.46	
11							

Fig.3.13: ABMO-1 Horizontal Well String Editor (Wellplan).


String Editor

String Initialization

String Type: Drill String | String Depth: 11048.0 ft | Specify: Top to Bottom

	Section Type	Length (ft)	Depth (ft)	OD (in)	ID (in)	Weight (ppf)	Catalog Description
1	Drill Pipe	4624.53	4624.5	5.000	4.276	22.60	DP 5 in, 19.50 ppf, S, NC50(XH), 1
2	Drill Pipe	3543.00	8167.5	5.000	4.276	22.60	DP 5 in, 19.50 ppf, S, NC50(XH), 1
3	Drill Pipe	2730.00	10897.5	5.000	4.276	22.60	DP 5 in, 19.50 ppf, S, NC50(XH), 1
4	Heavy Weight	30.00	10927.5	5.000	3.000	49.70	HW Grant Prideco, 5 in, 49.70 ppf
5	Jar	18.70	10946.2	6.500	2.750	91.79	JRH Dailey Hyd., 6 1/2 in
6	Heavy Weight	30.00	10976.2	5.000	3.000	49.70	HW Grant Prideco, 5 in, 49.70 ppf
7	Drill Collar	30.00	11006.2	6.750	3.000	96.71	DC 6 3/4 in, 3 in,
8	MWD	18.20	11024.4	6.750	3.000	97.73	MWD 6 3/4 , 6 3/4 x3 in
9	Sub	9.40	11033.8	6.720	3.000	97.72	XO 6 3/4, 6 3/4 x3 in
10	Mud Motor	13.35	11047.2	6.750	3.000	97.73	BHM 6 3/4 , 6 3/4 x3 in
11	Bit	0.82	11048.0	8.500		170.00	
12							

Fig.3.14: ABMO-1 ERD Well String Editor (Wellplan).

2.3.5.4 Survey Editor:

In Survey editor, MD, Inclination and Azimuth are inserted from the survey file in well Daily Drilling Report (DDR). The TVD, dogleg, Vertical section is calculated automatically as the MD, Inclination and Azimuth data inserted. As stated, the survey editor data can be found in appendix A in form of standard survey report, the figure below represents some of the data entered into survey editor.

Survey Editor

Identification

Name: ABMO-1 Description: Horizontal Well

	MD (ft)	INC (deg)	AZ (deg)	TVD (ft)	DLS (deg/100ft)	AbsTort (deg/100ft)	RelTort (deg/100ft)	VSect (ft)	North (ft)	East (ft)	Build (deg/100ft)	Walk (deg/100ft)
1	0.0	0.00	5.20	0.0	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
2	98.4	0.00	5.20	98.4	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
3	196.9	0.00	5.20	196.9	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
4	295.3	0.00	5.20	295.3	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
5	393.7	0.00	5.20	393.7	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
6	492.1	0.00	5.20	492.1	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
7	590.6	0.00	5.20	590.6	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
8	689.0	0.00	5.20	689.0	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
9	787.4	0.00	5.20	787.4	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
10	885.8	0.00	5.20	885.8	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
11	984.3	0.00	5.20	984.3	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
12	1082.7	0.00	5.20	1082.7	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
13	1181.1	0.00	5.20	1181.1	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
14	1279.5	0.00	5.20	1279.5	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
15	1378.0	0.00	5.20	1378.0	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
16	1476.4	0.00	5.20	1476.4	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
17	1574.8	0.00	5.20	1574.8	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
18	1673.2	0.00	5.20	1673.2	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
19	1771.7	0.00	5.20	1771.7	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
20	1870.1	0.00	5.20	1870.1	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
21	1968.5	0.00	5.20	1968.5	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
22	2066.9	0.00	5.20	2066.9	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
23	2165.4	0.00	5.20	2165.4	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
24	2263.8	0.00	5.20	2263.8	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
25	2362.2	0.00	5.20	2362.2	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
26	2460.6	0.00	5.20	2460.6	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
27	2559.1	0.00	5.20	2559.1	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
28	2657.5	0.00	5.20	2657.5	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
29	2755.9	0.00	5.20	2755.9	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
30	2854.3	0.00	5.20	2854.3	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
31	2952.8	0.00	5.20	2952.8	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
32	3051.2	0.00	5.20	3051.2	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00
33	3149.6	2.40	5.20	3149.6	2.44	0.08	0.00	2.1	2.1	0.2	2.44	0.00

Fig.3.15: ABMO-1 Horizontal and ERD Wells Survey Editor (Wellplan).

2.3.5.5 Fluid Editor:

Fluid editor options enable the user to input the fluid used in the drilling such as: rheology properties, mud base and other mud properties.

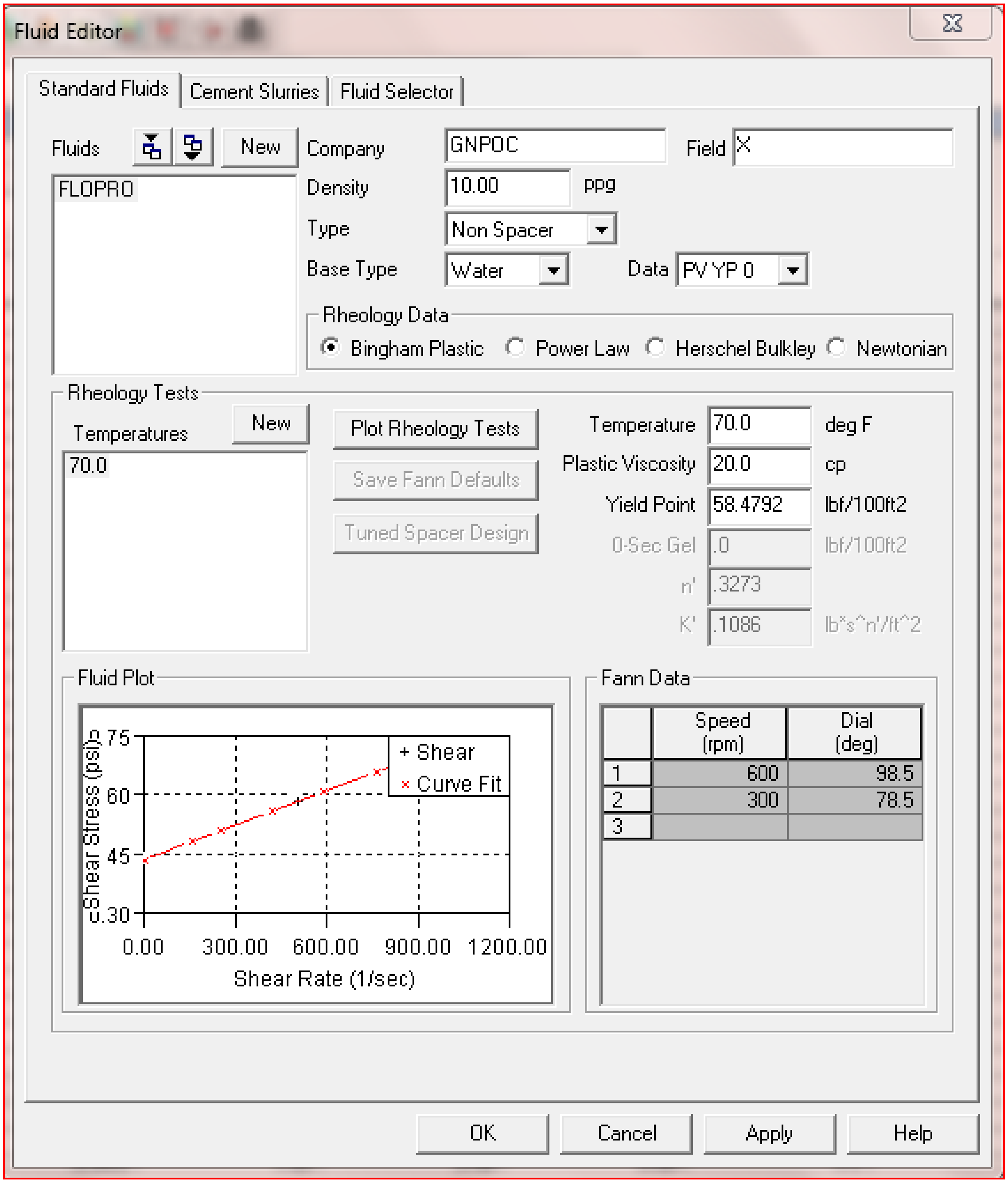


Fig.3.16: ABMO-1 Horizontal Well Fluid Editor (wellplan).

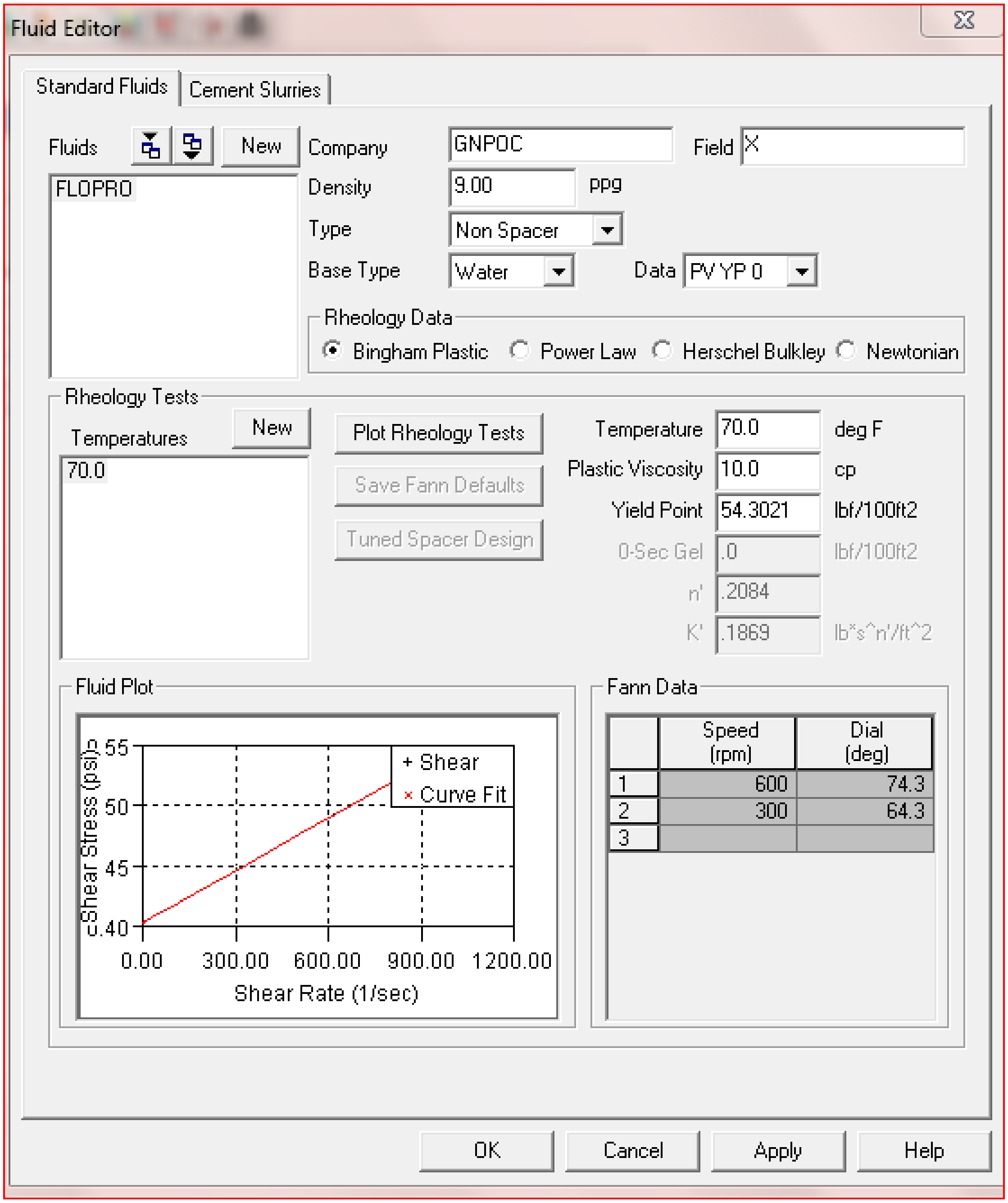


Fig.3.17: ABMO-1 ERD Well Fluid Editor (wellplan).

2.3.5.6 Wellplan Torque and Drag Analysis Module:

Wellplan T&D Analysis module can be used to predict the measured weights and torques to be expected while tripping in, tripping out, rotating on bottom, rotating off bottom, slide drilling, and backreaming. This information can be used to determine if the well can be drilled, or to evaluate hole conditions while drilling a well. The module can be used for analyzing drillstrings, casing strings, and liners.

To determine the analysis specifications for T&D analysis, T&D setup dialog, fig.3.18, is used to specify the use of either the soft or stiff string model in the analysis.

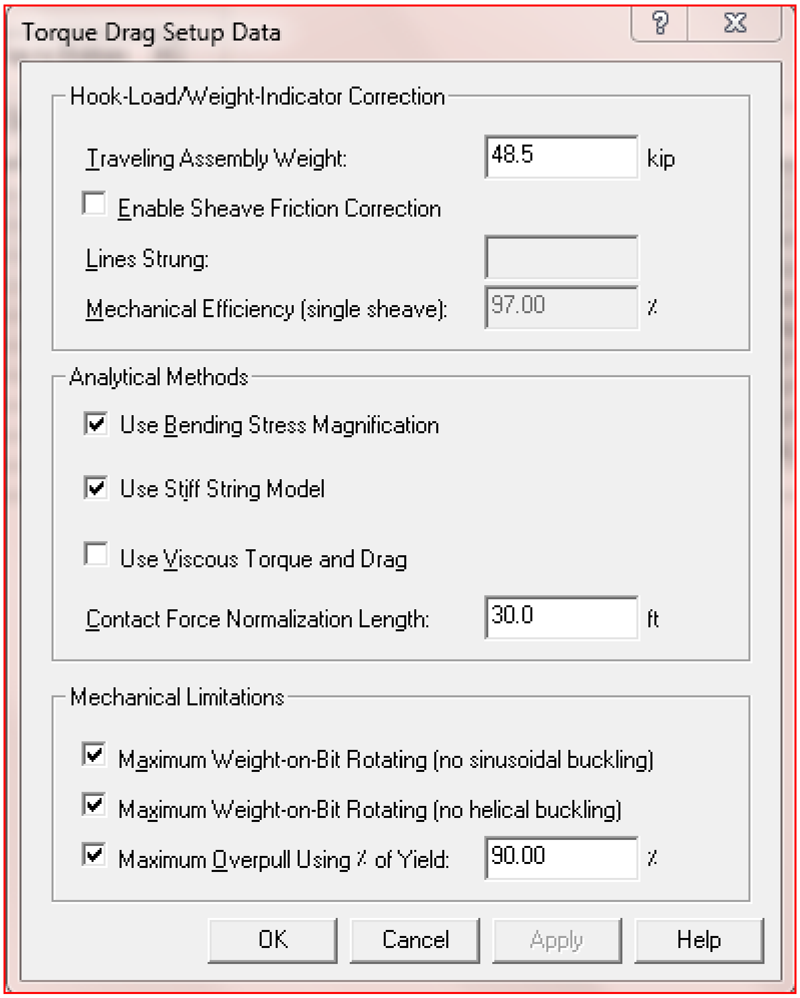


Fig.3.18: ABMO-1 Horizontal and ERD Wells T&D Setup Data (Wellplan).

The T&D Module has four available analysis modes. In this project only three of the analysis modes will be investigated. The next paragraphs include an explanations of the analysis modes covered in this project in addition to the data inputted to each of them:

2.3.5.6.1 Calibrate Coefficient of Friction:

As mentioned previously, friction coefficient cannot be precisely determined. Calibrate coefficient of friction provides a mean to calculate the coefficient of friction along the wellbore from actual data collected while drilling. This provides a means of calibrating the model against actual field result. Coefficient of friction in the casing section must be calculated first, then the openhole. This is required because data recorded in the openhole section includes the combined effects of friction between the string and the casing as well as the friction between the string and the openhole. Therefore, the coefficient of friction for the cased hole must be determined before that of the open hole.

Actual Loads dialog, fig.3.19, is used to record actual load data encountered at certain depths. This information can be used to calculate coefficients of friction using the Calibrate Friction analysis or it can be displayed in the Drag Chart analysis graphs to compare actual values with calculated values. The figure below shows the Calibration Data dialog to specify parameters required to calibrate the coefficients of friction for cased hole and open hole section.

Actual Loads

		Measured Weight				Torque	
	Bit Depth (ft)	Trip In (kip)	Trip Out (kip)	Off Bottom (kip)	Slide (kip)	On Bottom (ft-lbf)	Off Bottom (ft-lbf)
1	3782.0	125.7	130.1	127.9		1080.0	
2	4467.4	127.9	132.3	130.1		1160.0	
3	5192.2	138.9	149.9	143.3		1260.0	
4	5677.7	138.9	147.7	143.3		1570.0	
5	5969.6	136.7	154.3	143.3		1450.0	
6	6481.3	136.7	156.5	143.3		1800.0	
7	6724.0	127.9	176.4	149.9		1870.0	
8	6904.4	121.2	136.7	132.3		2370.0	
9	7708.0	130.1	143.3	141.1		2890.0	
10							

Fig.3.19: ABMO-1 Horizontal Well actual Loads (Wellplan).

2.3.5.6.2 Normal Analysis:

Normal analysis calculates the torque, drag, normal force, axial force, buckling force, neutral point, stress and other parameters for a work string in a three dimensional wellbore. With a normal analysis, all calculations are performed with the bit at one position in the wellbore with one set of operational parameters.

Normal analysis mode calculates the forces acting along the string and at the surface for several operating conditions including: tripping in, tripping out, rotating on bottom, rotating off bottom, and backreaming. Based on the API material specifications of pipe class, material, and grade, the following special load cases are also calculated: Maximum weight on bit to avoid sinusoidal buckling, maximum weight on bit to avoid helical buckling, and Maximum overpull to not exceed yield while tripping out of hole. Normal analysis mode uses the information input on the Case menu in addition to other data as can be seen in the normal analysis mode data in fig.3.20 below.

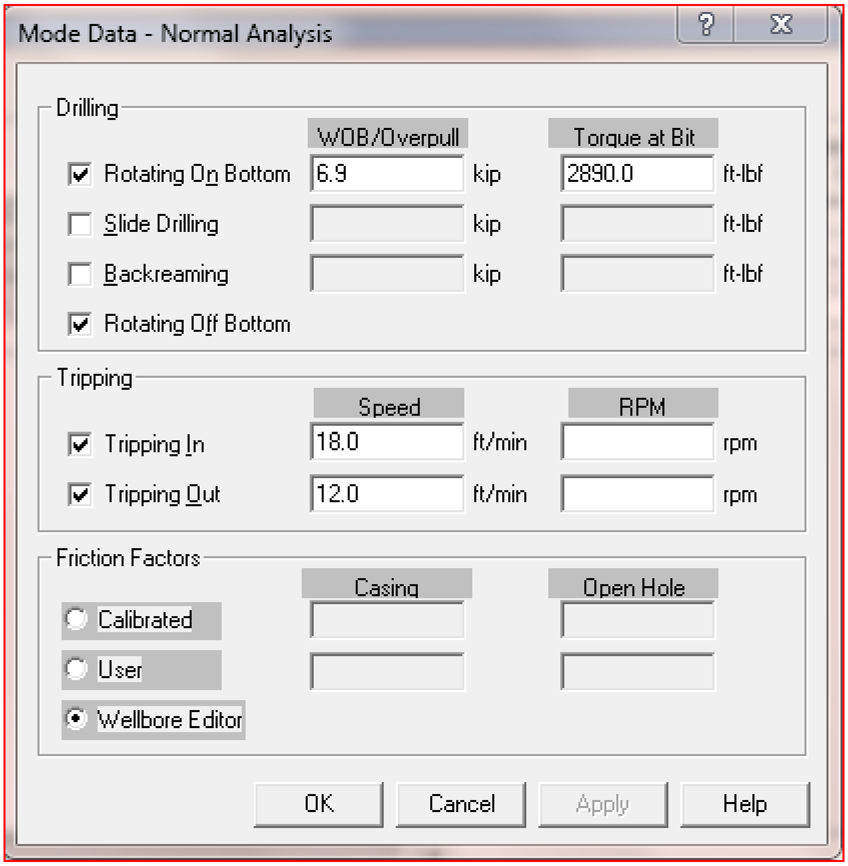


Fig.3.20: ABMO-1 horizontal Well Normal Analysis Mode Data (Wellplan).

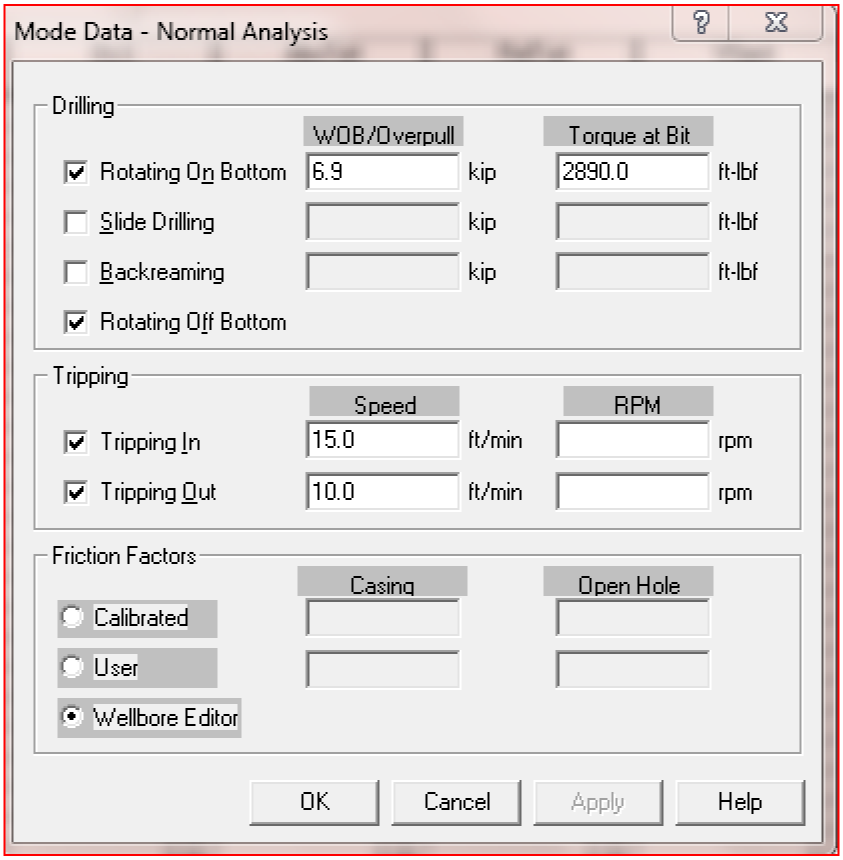


Fig.3.21: ABMO-1 ERD Well Normal Analysis Mode Data (Wellplan).

Results for a Normal Analysis are presented in tables, plots, and reports. In this project, only plots will be used to display the results. There are several plots containing analysis results for a normal analysis. These include:

Effective Tension Plot:

The Effective Tension plot displays the tension in all sections of the work string for the operating modes specified on the normal analysis mode data dialog calculated using the buoyancy method. The graph includes data for measured depths from the surface to the string depth specified on the String Editor. The effective tension can be used to determine when buckling may occur. On the plot there are curves indicating the loads required to buckle the work string. When the effective tension load line for a particular operation mode crosses a buckling load line, the string will begin to buckle in the buckling mode corresponding to the buckling load line.

The plot also indicates the tension limit for the work string component at the corresponding measured depth. If the effective tension curve for a particular operating mode exceeds the tension limit curve, the work string is in danger of parting at that point.

True Tension Plot:

The True Tension plot displays the tension in all sections of the work string for the operating modes specified on the normal analysis mode data dialog as calculated using the pressure area method. The graph includes data for measured depths from the surface to the string depth specified on the String Editor.

There are other plots in normal analysis mode include:

- Torque plot
- Side force plot
- Fatigue graph

2.3.5.6.3 Drag Charts:

Drag chart analysis is used to predict the measured weights and torques that will be experienced while operating the work string at a range of depths in the wellbore. The calculations performed for this analysis are similar to those used in the Normal Analysis except the calculations are performed over a range of depths.

In drag charts, the run parameters dialog is used to specify the analysis parameters for a drag chart analysis. On this dialog the depth interval that you want to analyze is indicated in addition to the operation modes that want to be analyzed.

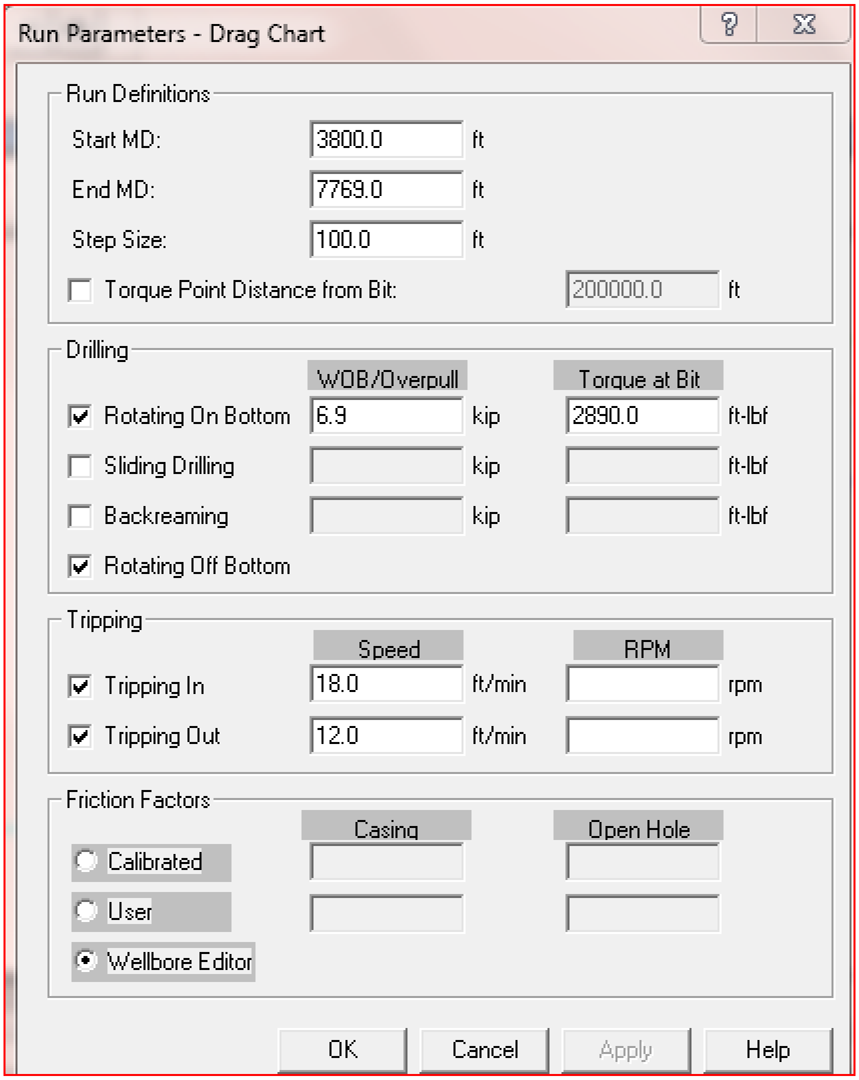


Fig.3.22: ABMO-1 horizontal well drag chart run parameters (Wellplan).

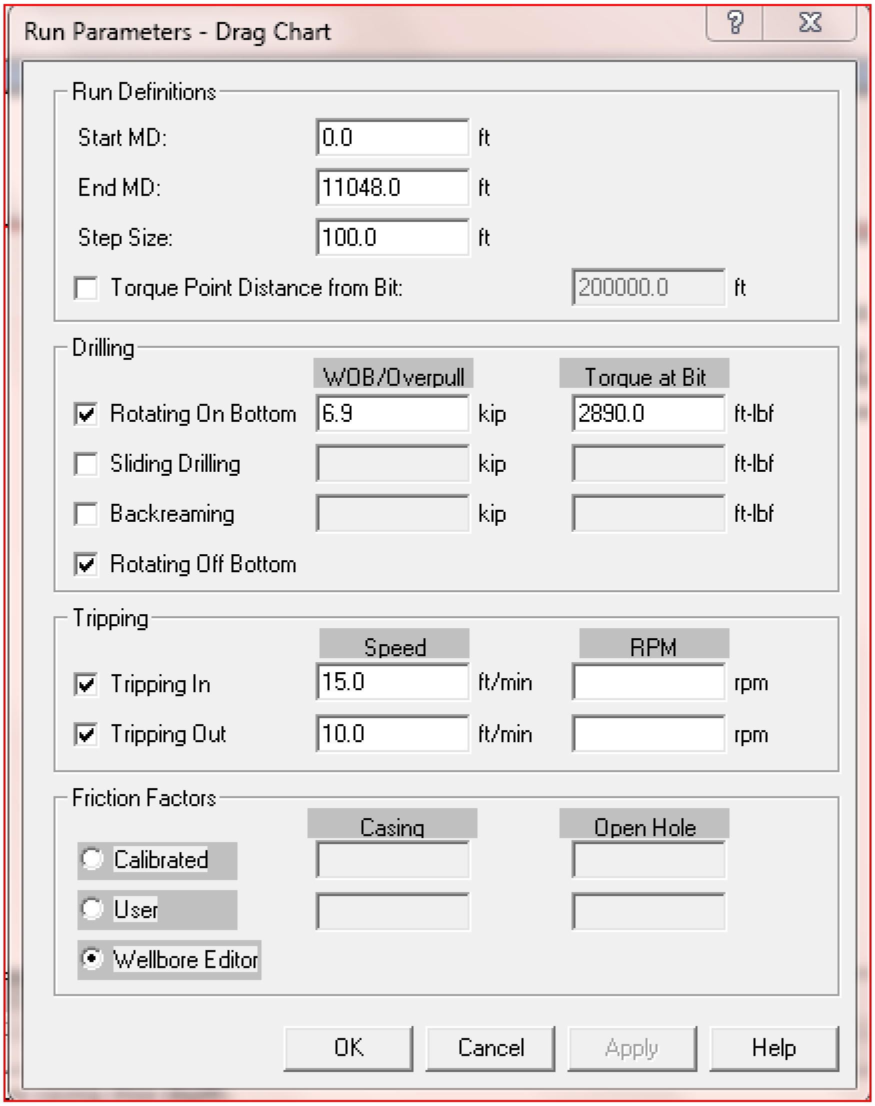


Fig.3.23: ABMO-1 ERD Well Drag Chart Run Parameters (Wellplan).

It should be noted that the results from drag chart are only displayed in form of plots. These plots include:

Measured Weight Chart:

The Measured Weight chart shows measured weights for all operating modes selected on the Run Parameters dialog. This analysis covers only the measured depth interval specified on the run parameters dialog.

Torque Point Chart:

The Torque Point chart displays the maximum torque found at the surface, or at a user specified point in the work string for all rotary operating modes selected on the Run Parameters dialog. The Torque Point chart covers only the measured depth interval specified on the Run Parameters dialog.

Minimum Weight on Bit Chart:

This chart displays minimum weight on bit to start helical or sinusoidal buckling.

Chapter Four

Results and Discussion

4.1 ABMO-1 Horizontal Well Torque and Drag Analysis:

The well selected for the case study is a horizontal well drilled in the field X, block 2b. It was drilled from the drilling rig Y to TD at 7767ft MD. A 9.625 inch casing was set to 6756ft MD. And a 7 inch liner was set from 6725ft MD to 7767ft MD as can be seen in the geometry of this well in fig.4.1. Fig.4.2 through fig.4.5 shows the vertical section versus TVD, azimuth versus MD, inclination versus MD, and DLS versus MD respectively.

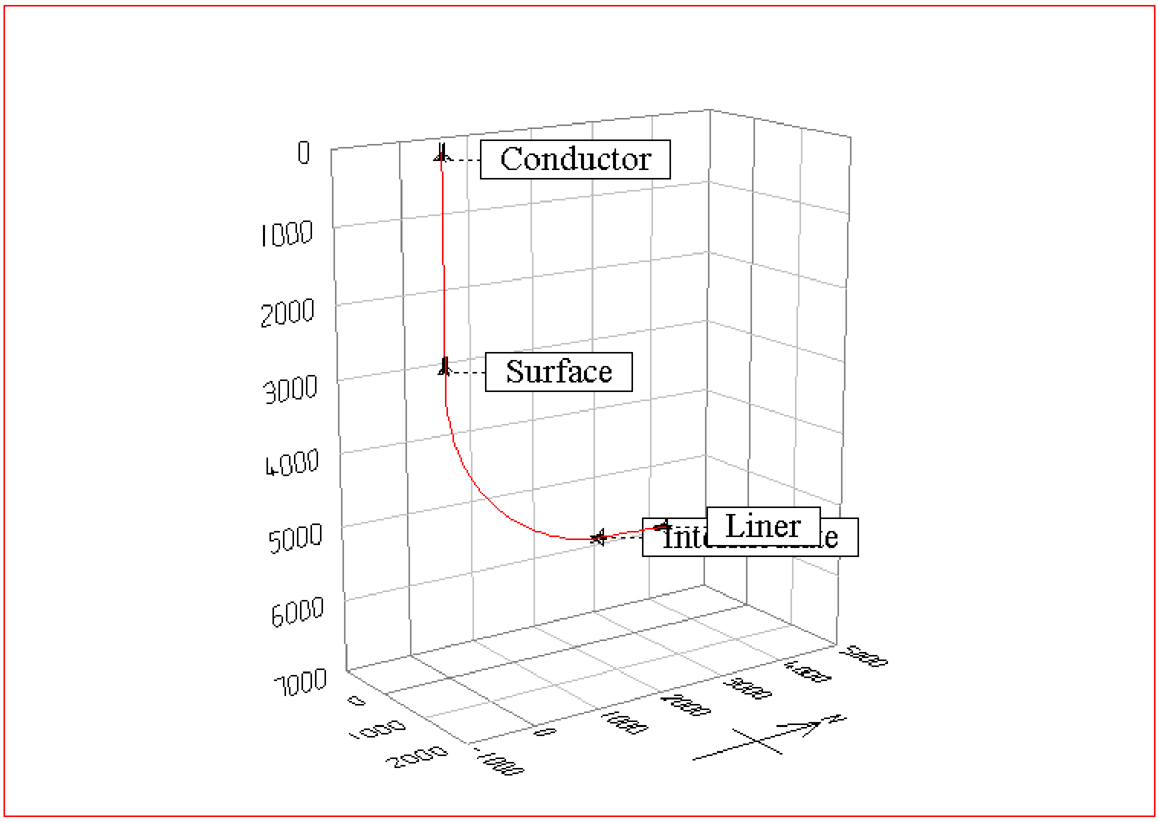


Fig.4.1: ABMO-1 Horizontal Well Geometry (Compass).

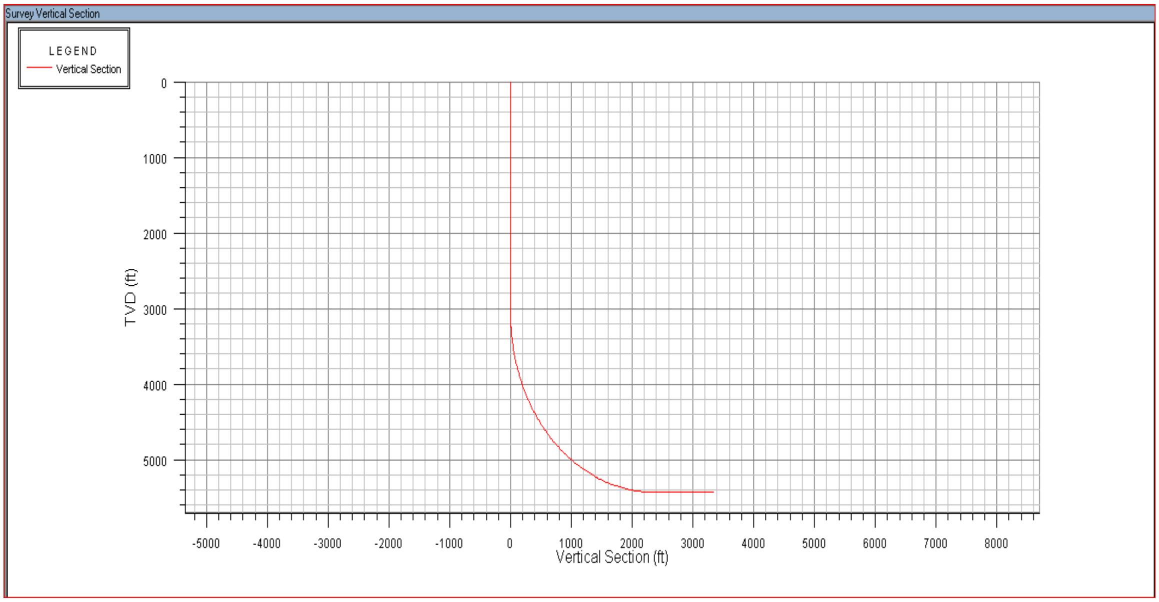


Fig.4.2: ABMO-1 Horizontal Well Vertical Section (Wellplan).

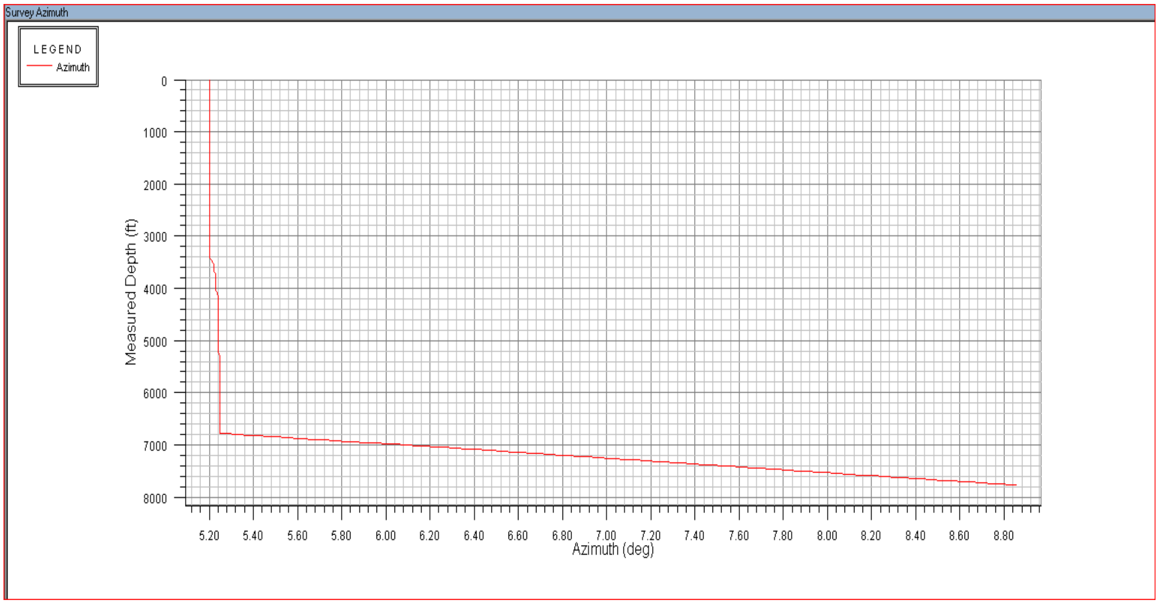


Fig.4.3: ABMO-1 Horizontal Well Azimuth (Wellplan).

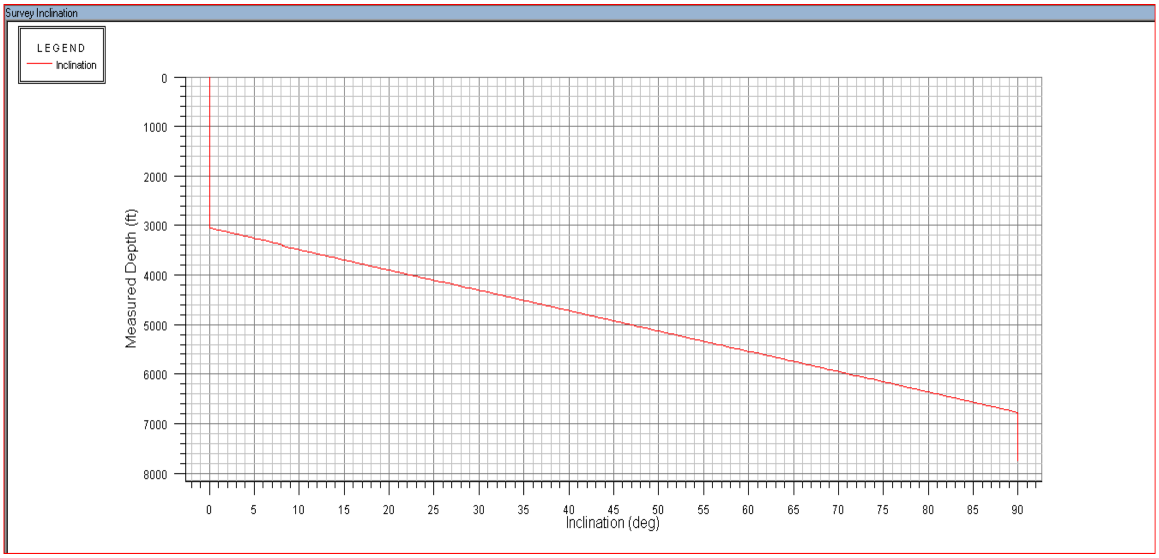


Fig.4.4: ABMO-1 Horizontal Well Inclination (Wellplan).

The dogleg severity in this well is not very large, with a maximum of 2.45 degree/100ft at 3100ft MD, as shown in Figure 5.6.

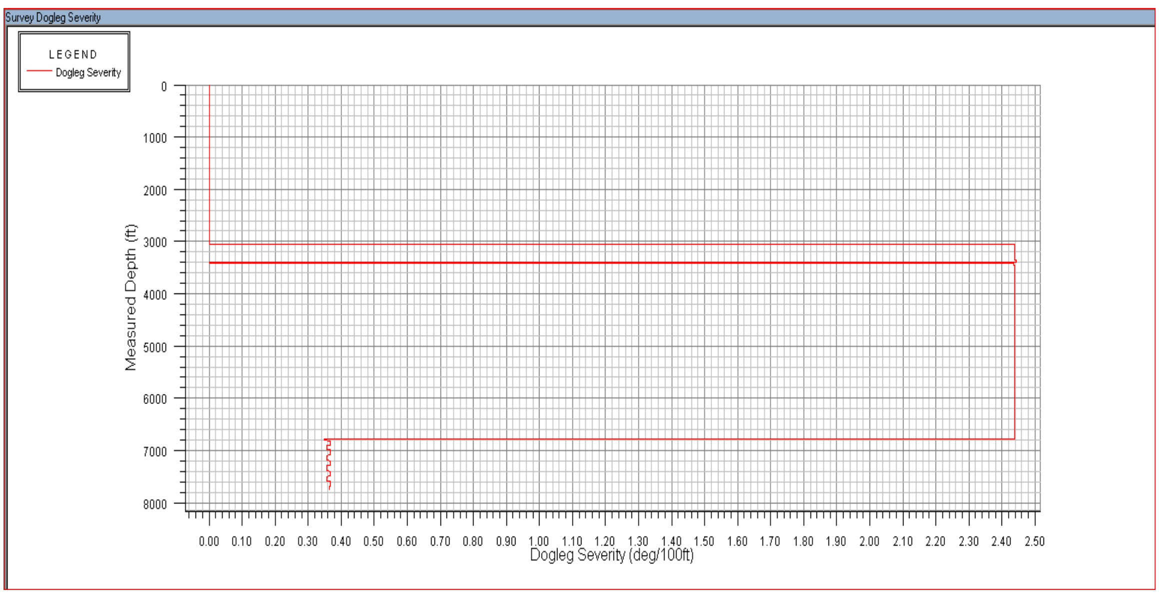


Fig.4.5: ABMO-1 Horizontal Well DLS (Wellplan).

4.1.1 Calibrate Coefficient of Friction:

The analysis results show that the friction factor for cased hole is found to be 0.26 as can be seen in fig.4.6 below. But due to lack of sufficient and accurate data for operating conditions in the openhole section, the friction factor for openhole section is assumed to be 0.32.

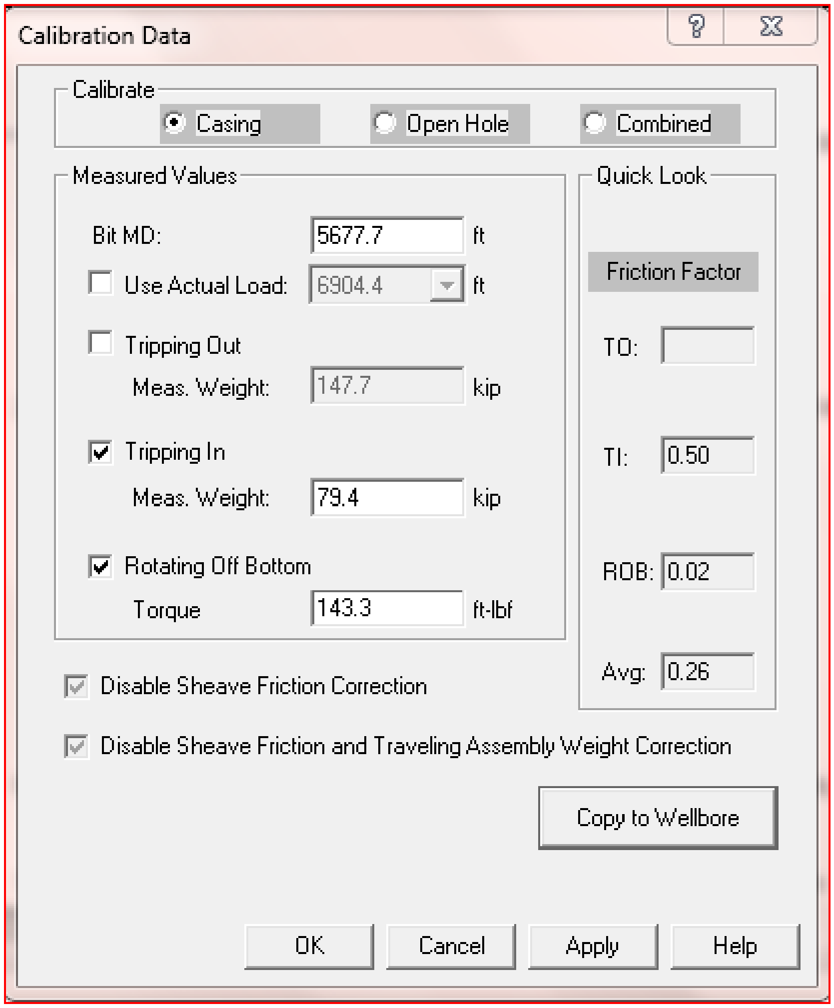


Fig.4.6: ABMO-1 Horizontal Well Coefficient of Friction Calibration Data (Wellplan).

4.1.2 Normal Analysis:

4.1.2.1 Effective Tension Plot:

As stated previously, the effective tension plot is used to determine when buckling may occur. With referencing to fig.4.7 below, since the tripping in and tripping out load lines do not cross the buckling load lines at any point or depth along the hole, then there is no possibility of buckling, sinusoidal or helical, along the entire length of the drillstring but, some care should be developed during tripping in at 2800ft to 3100ft MD, since the drillstring at these points is close to the buckling.

Also the tension limit of the string components is not exceeded at any depth or point along the entire hole thus, there is no danger of drillstring parting at any depth.

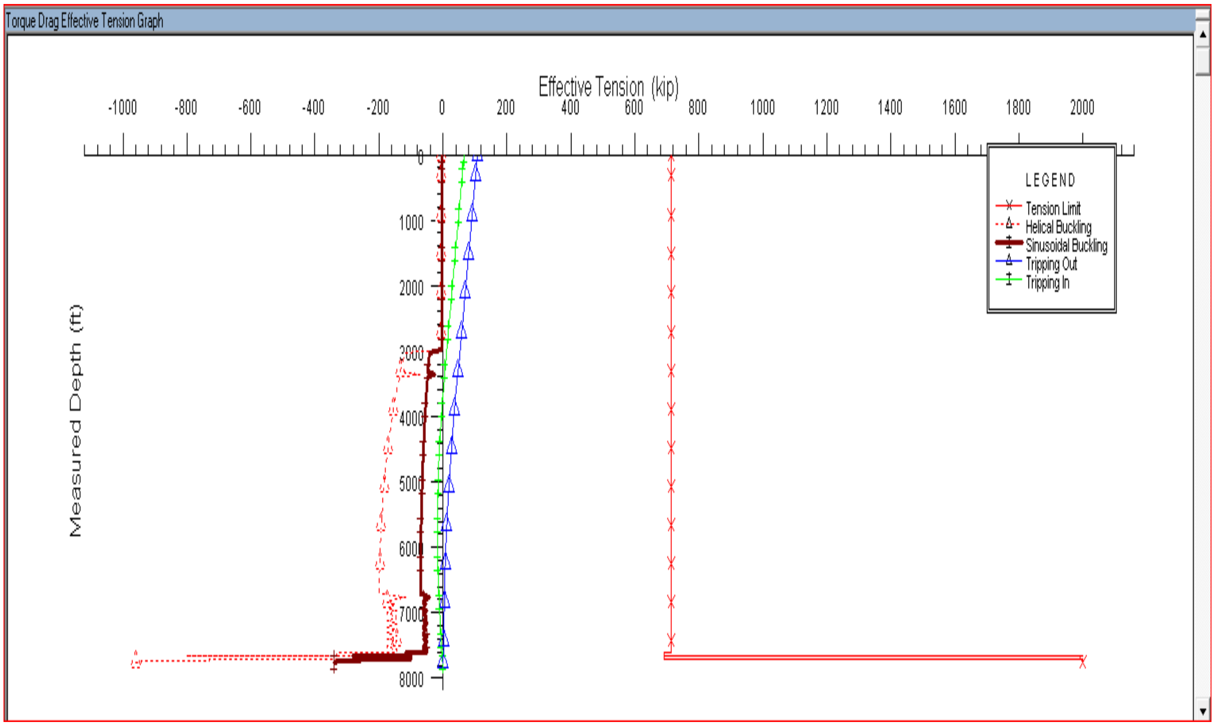


Fig.4.7: ABMO-1 Horizontal Well Effective Tension during Tripping in and Tripping out (Wellplan).

Figure below, fig.4.8, shows the effective tension acting along the all sections of the drillstring during the rotating on and off bottom operations. Also there is no possibility of buckling or parting along the entire length of drill string. But some degree of caring should be developed during rotate on bottom at 3000ft MD and at 6780ft MD.

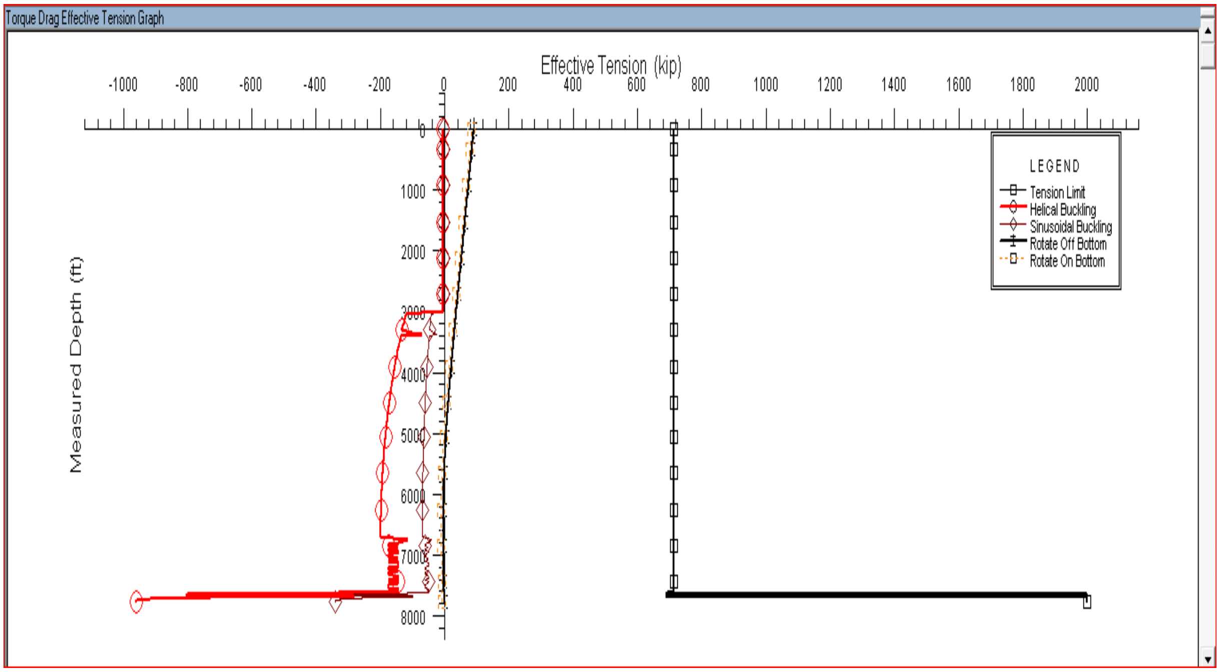


Fig.4.8: ABMO-1 Horizontal Well Effective Tension during Rotating on and off bottom (Wellplan).

4.1.2.2 Torque Plot:

As can be seen in figure below, torque is displayed in all sections of the drillstring for the tripping in, tripping out, rotate on bottom, and rotate off bottom operations. It is obviously that the torque at surface during the rotating on bottom operation is greater than that of the rotating off bottom operation. Torque at the surface starts to decline with depth due to the rotational friction forces until reach the minimum value at the bit which is known as torque on bit (TOB).

It should be noted that the torque values during the tripping in and tripping out operations are equal to zero due to the fact that there is no rotation in the drillstring. Also since all the displayed torque curves during different operation modes do not exceed the makeup torque limit, the tool joints for the drillstring are not liable to over torque or break.

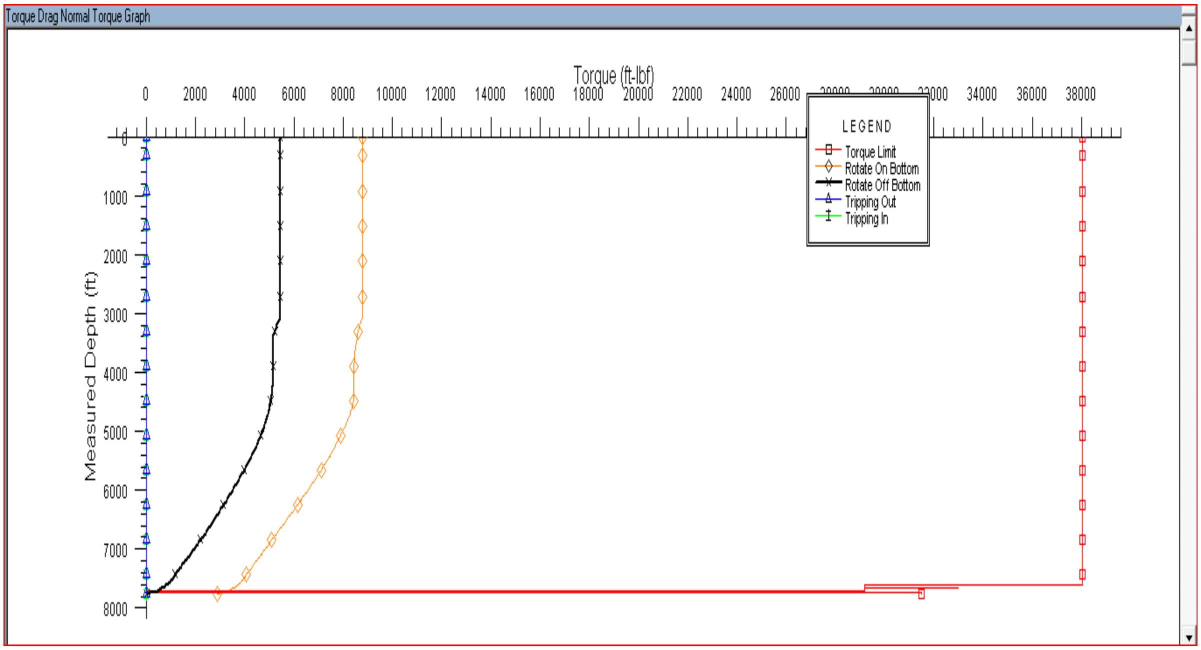


Fig.4.9: ABMO-1 Horizontal Well Torque Plot (Wellplan).

4.1.3 Drag Chart Analysis:

4.1.3.1 Measured Weight Chart:

Figure below shows the weights encountered during the drilling of ABMO-1 horizontal well for the tripping out operation mode along with the calculated weights using wellplan software. It is obvious that there is a relatively good match between the actual and calculated weights from the surface until approximately 5800ft MD from which the actual and calculated weights differ and then match again at 6800ft MD then differ again to the end.

The measured weights at 5800ft is greater that the calculated values using wellplan software. This is may be due to inaccuracy in measuring loads encountered during the drilling of the well or due to the fact that the well angle is continued to be increased beyond 67degrees which increase the curvature of the hole. The measured weight at 6800ft is less than the calculated values and this is due to the fact that the well inclination at this depth is 90 degree. It should be noted that the measured and calculated weights lie between the minimum weight for helical buckling and maximum weight yield at any bit depth along the hole, thus there is no possibility of buckling.

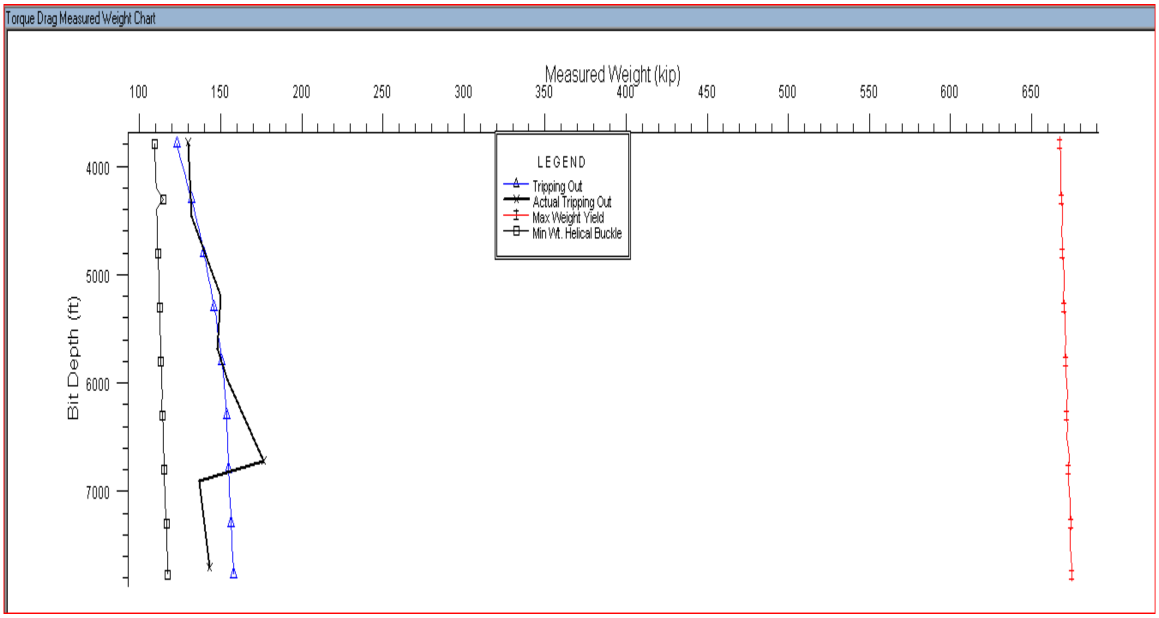


Fig.4.10: ABMO-1 Horizontal Well Measured and Calculated Weights during the Tripping out (Wellplan).

Figure below shows the weights encountered during the drilling of ABMO-1 horizontal well for the rotate off bottom operation mode along with the calculated weights using wellplan software. It is clear that the values of actual and calculated weights tend to be the same over a great portion of the well. The differences appear to be at 6700ft and 6900ft MD due to the fact that the well is horizontal in this section.

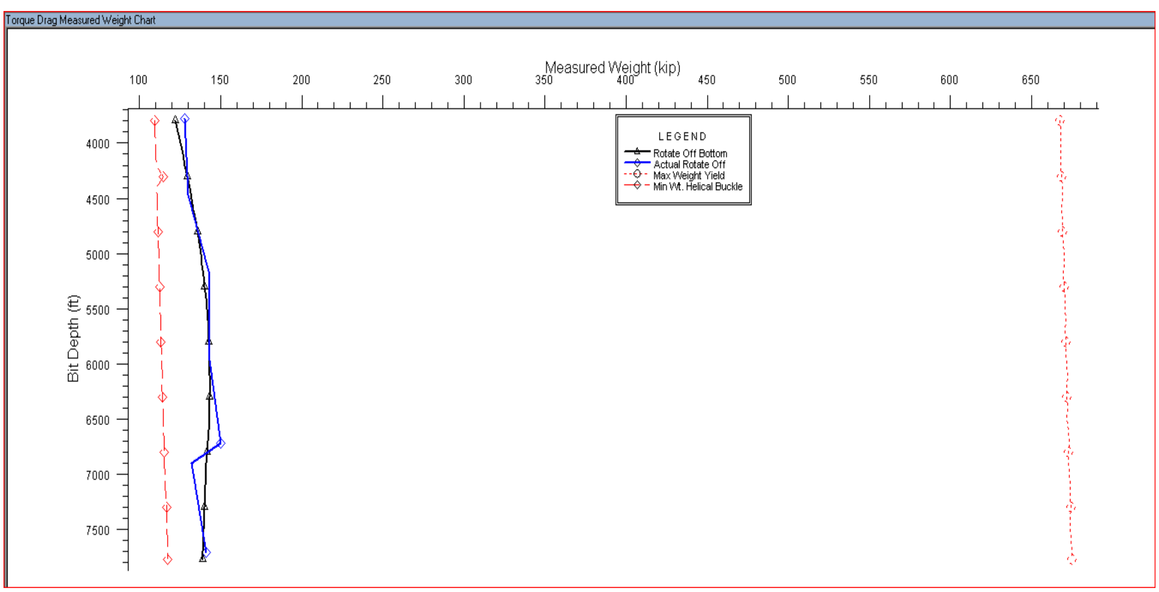


Fig.4.11: ABMO-1 Horizontal Well Measured and Calculated Weights during the Rotating off bottom (Wellplan).

Fig4.12 shows the weights encountered during the drilling of ABMO-1 horizontal well for the tripping in operation mode along with the calculated weights using wellplan software. It is obvious that the actual and calculated values are within the same limits except for calculated tripping in weight at 7200ft which is lower than the measured weight. Also the calculated weight shows the possibility of helical buckling at the bit depth corresponding to 7070ft which is not the case in actual weights. Any way care must be developed to ensure that the drillstring is not subjected to buckling at this bit depth.

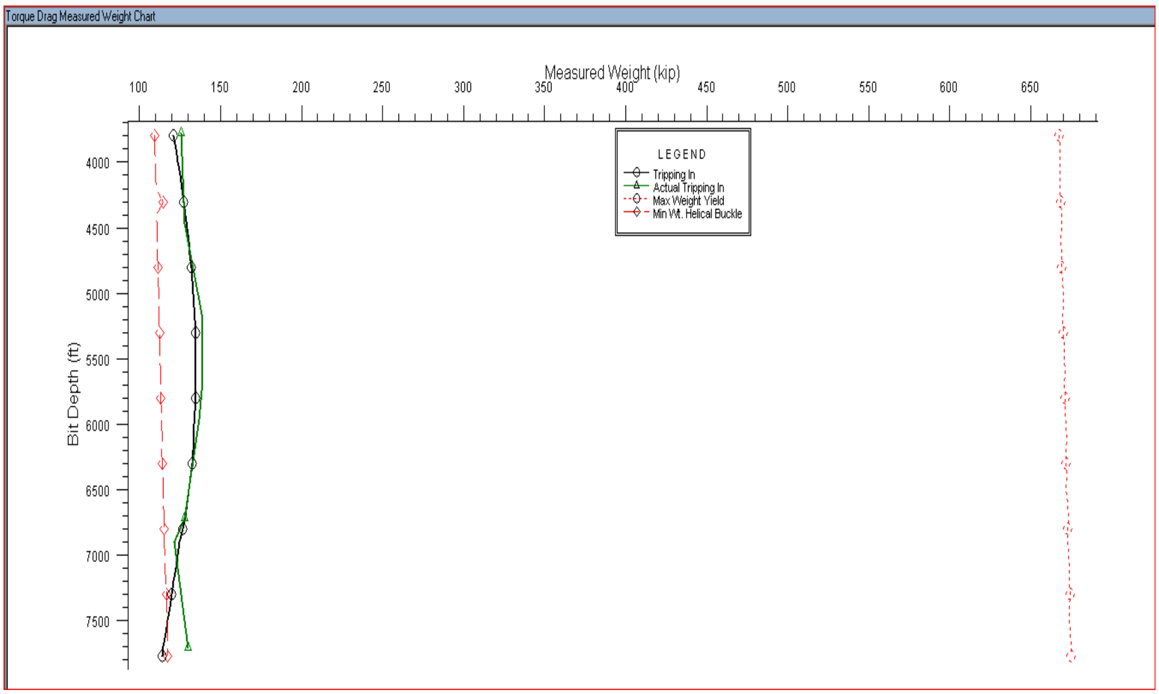


Fig.4.12: ABMO-1 Horizontal Well Measured and Calculated Weights during the Tripping in (Wellplan).

4.1.3.2 Torque Point Chart:

With reference to the torque point chart, fig.4.13, below, it is obvious that the torque at depth increases as the bit depth increases. Torque when the bit at 3750ft is equal to 400ft-lbf and 3200ft-lbf for rotating off bottom and on bottom operation modes respectively and continue to increase with depth until reach the maximum values of 5000ft-lbf and 8800ft-lbf for rotating off bottom and rotating on bottom respectively.

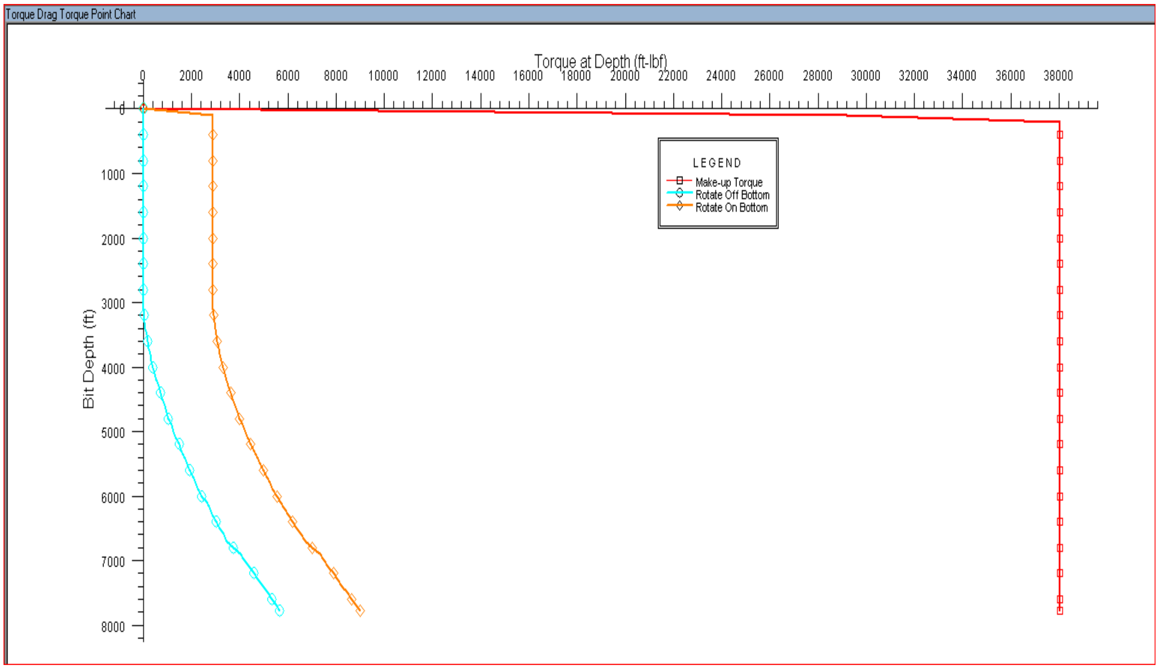


Fig.4.13: ABMO-1 Horizontal Well Torque Point Chart (Wellplan).

4.1.3.3 Minimum Weight on Bit Chart:

Minimum WOB to initiate helical or sinusoidal buckling can be seen in figure below. During the drilling of the ABMO-1 horizontal well, extreme care should be developed to ensure that the WOB kept less than the values displayed in this figure at the corresponding bit depths. Once the WOB exceeds the minimum WOB at the corresponding bit depths, the drillstring will start buckling according to the corresponding buckling mode.

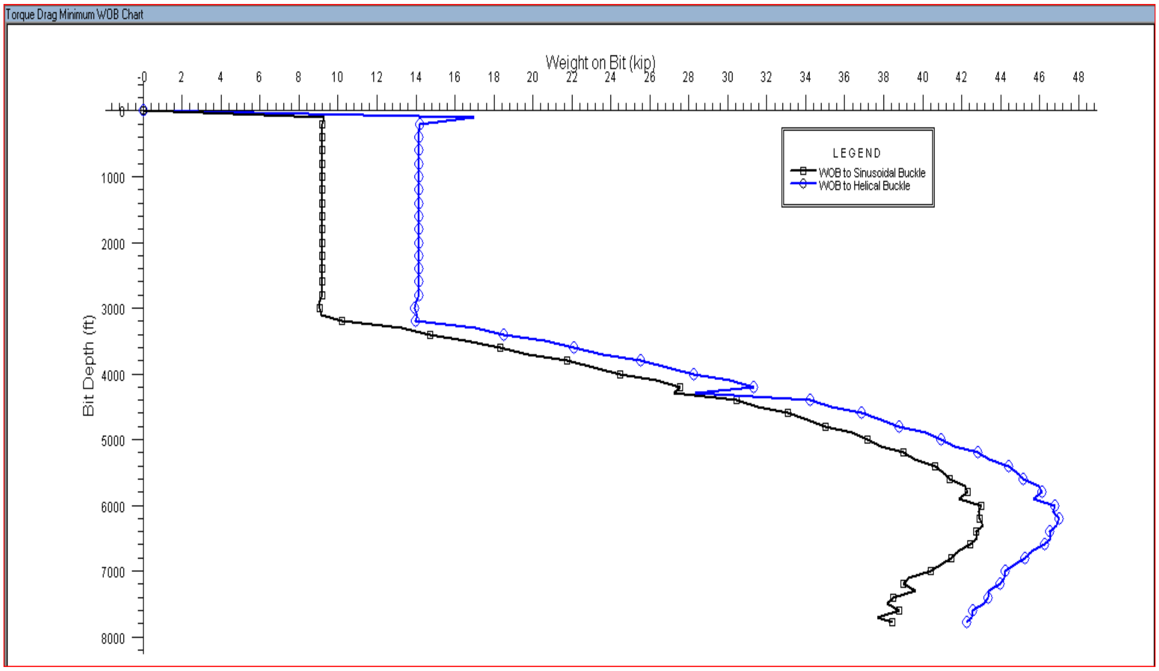


Fig.4.14: ABMO-1 Horizontal Well Minimum WOB Chart (Wellplan).

4.2 ABMO-1 ERD Well Torque and Drag Analysis:

As stated previously, this well results from the extension of the horizontal section of ABMO-1 horizontal well by about 3280ft.The geometry of this well can be seen in fig.4.15. Fig.4.16 through fig.4.18 shows the vertical section versus TVD, azimuth versus MD, inclination versus MD, and DLS versus MD respectively.

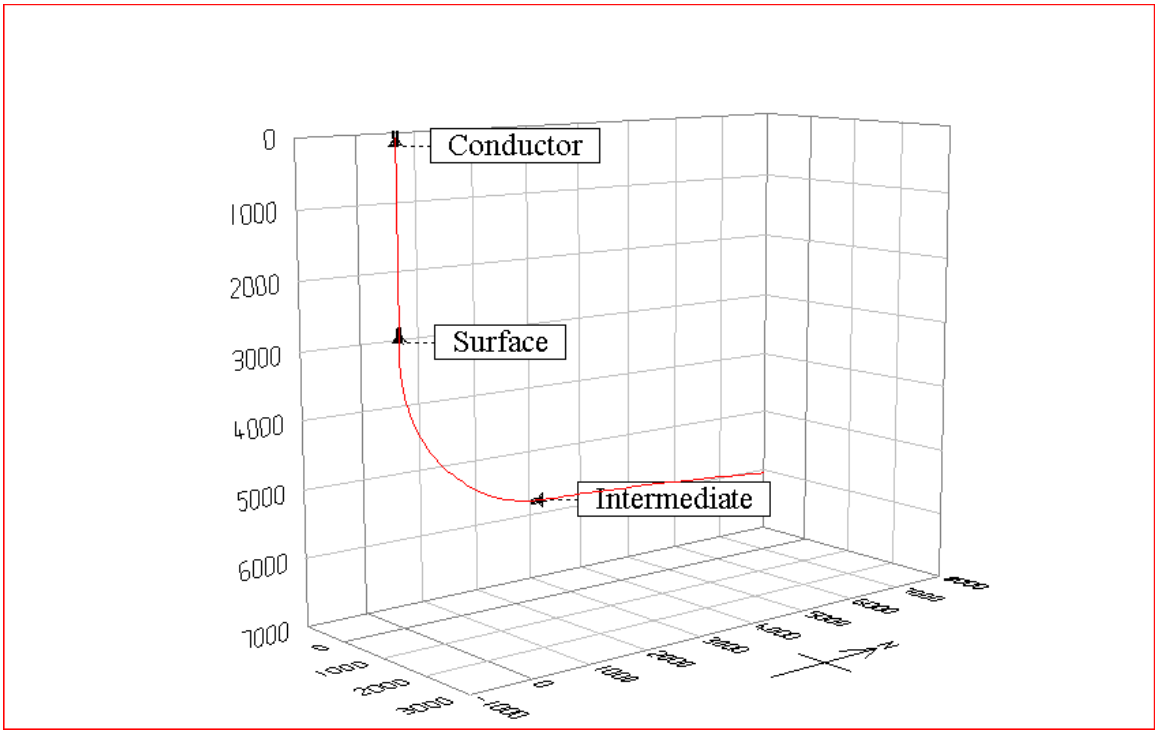


Fig.4.15: ABMO-1 ERD Well Geometry (Compass).

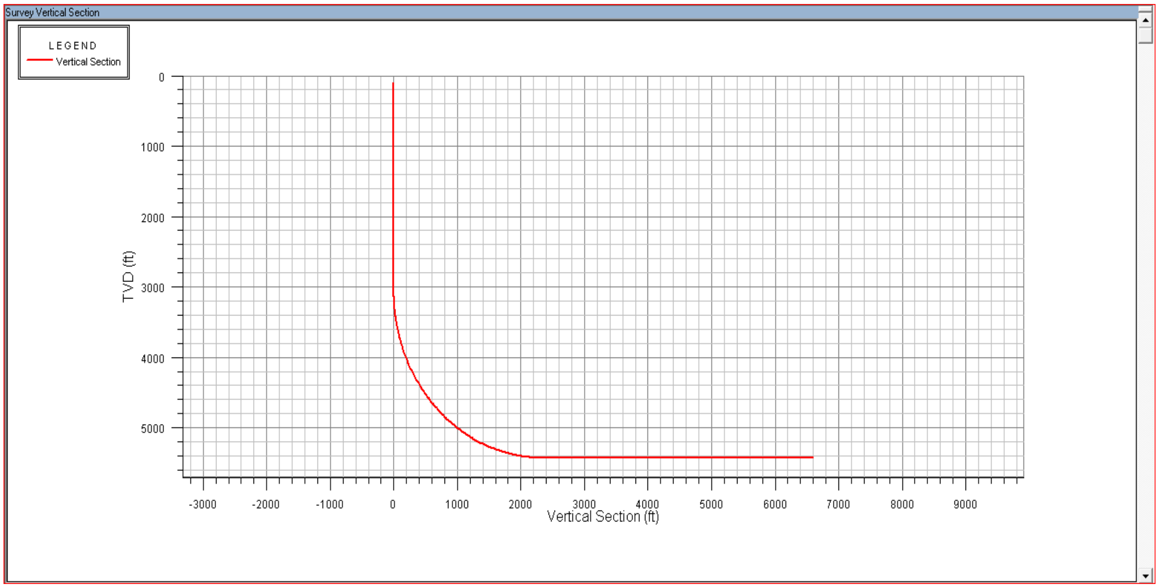


Fig.4.16: ABMO-1 ERD Well Vertical Section (Wellplan).

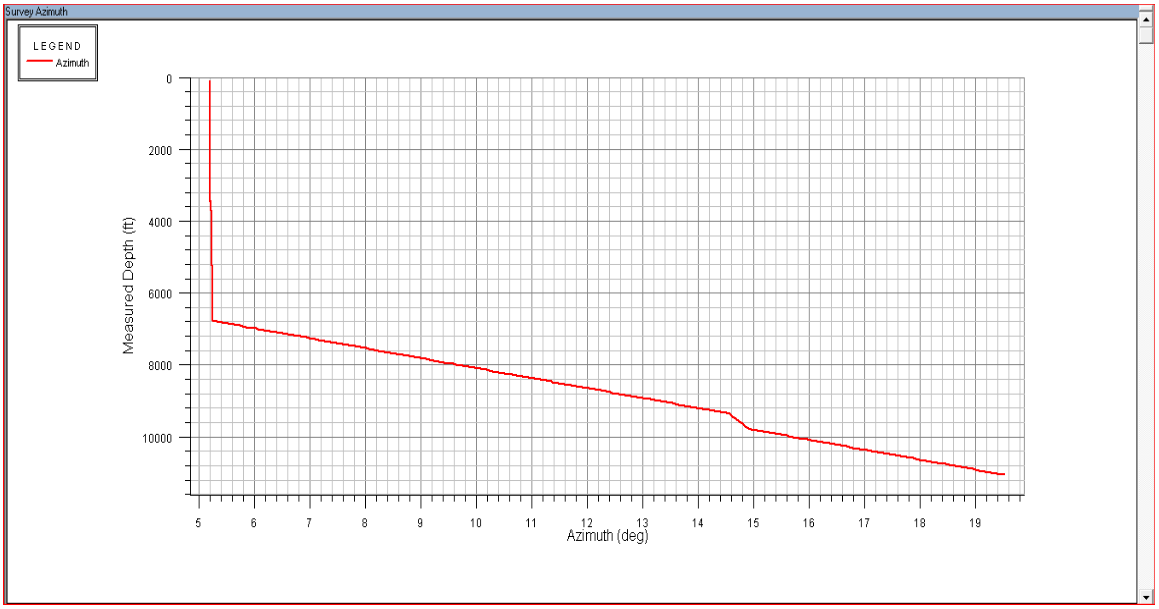


Fig.4.17: ABMO-1 ERD Well Azimuth (Wellplan).

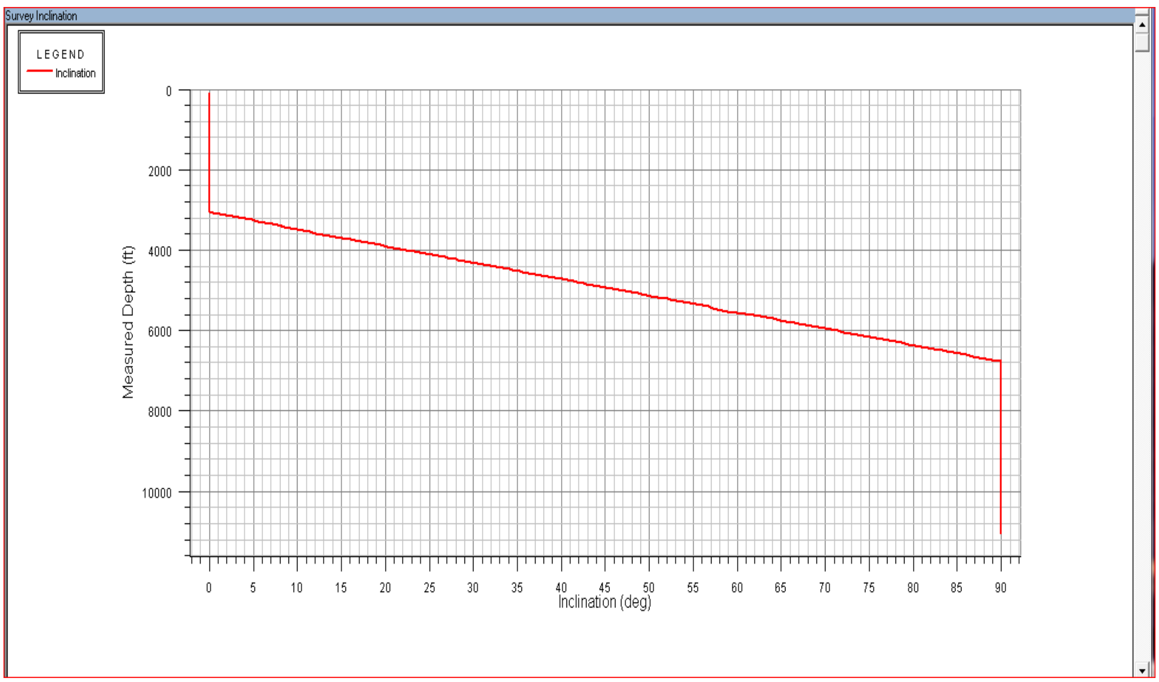


Fig.4.18: ABMO-1 ERD Well Inclination (Wellplan).

As can be seen in DLS graph, the DLS for ABMO-1 ERD well is relatively large compared to that of ABMO-1 horizontal well. Approximately equals 3.4 degree/100ft at 5600ft MD.

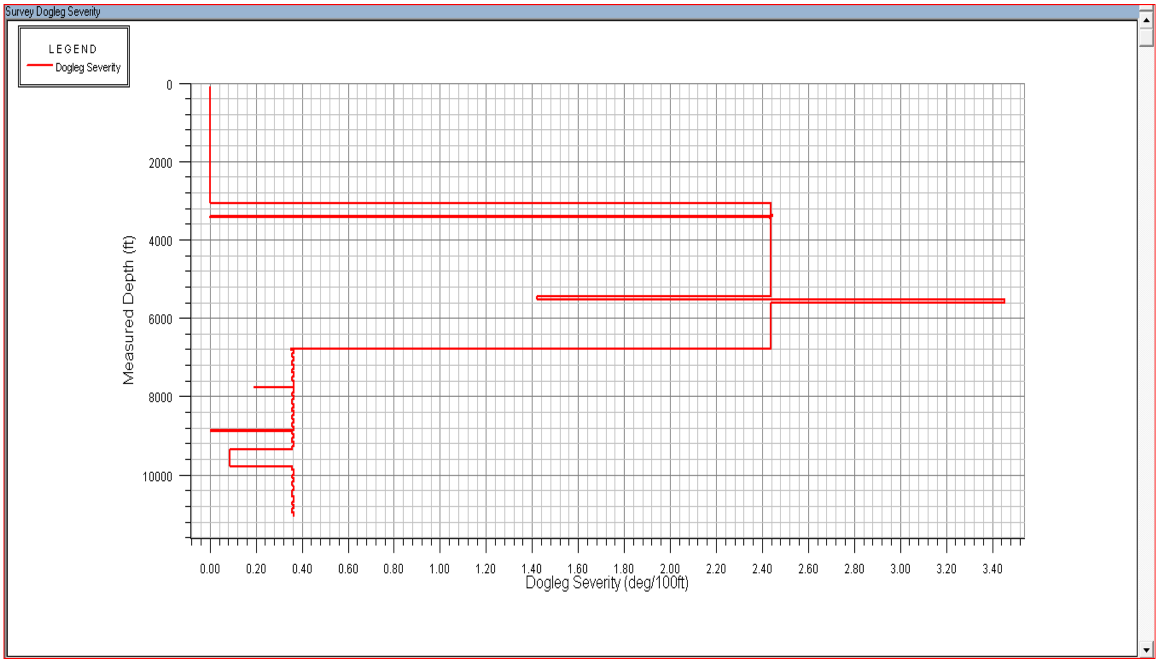


fig.4.19: DLS for ABMO-1 ERD Well (Wellplan).

4.2.1 Calibrate Coefficient of Friction:

The friction coefficient for ABMO-1 ERD well is assumed to be the same as for ABMO-1 horizontal well. For cased hole the friction factor equals to 0.26 while the openhole friction factor is assumed to be 0.32.

4.2.2 Normal Analysis:

4.2.2.1 Effective Tension Plot:

Fig.4.20 shows the effective tension acting along the drillstring along the hole during tripping in and tripping out operations. With reference to this figure, it is clear that during the tripping in operation from surface till 2800ft MD there is no possibility of drillstring buckling. But, from 2800ft MD to 3200ft MD the drillstring starts to buckle according to sinusoidal buckling mode then turns into helical buckling mode. Again at 6800ft MD the drillstring is very close to buckle therefore, extreme care must be developed to make sure that the drillstring will not buckle at these depths.

As a solution to the drillstring buckling from 2800ft to 3200ft MD the friction between the drilltring and borehole must be reduced by using heavier mud or, instead, to replace the drillpipe from the surface to 3650ft MD with heavy weight drillpipe (HWDP). Fig.4.21

shows the tripping in effective tension if the 3650ft MD HWDP replace the drillpipe which is well within it is boundaries. Again, extreme care should be developed to make sure that the drillstring will not buckle at that section.

During the tripping out operation there is no possibility to buckle the drillstring because the effective tension curve during tripping out does not cross any of the buckling curves.

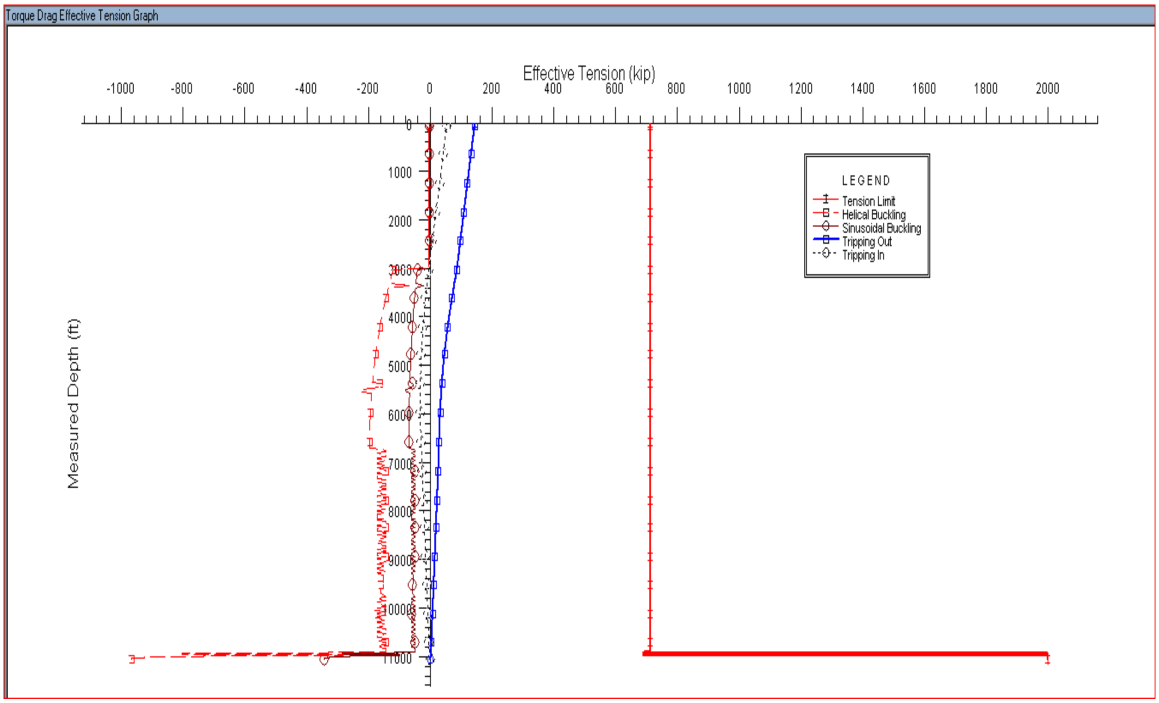


Fig.4.20: ABMO-1 ERD Well Effective Tension during Tripping in and Tripping out (Wellplan).

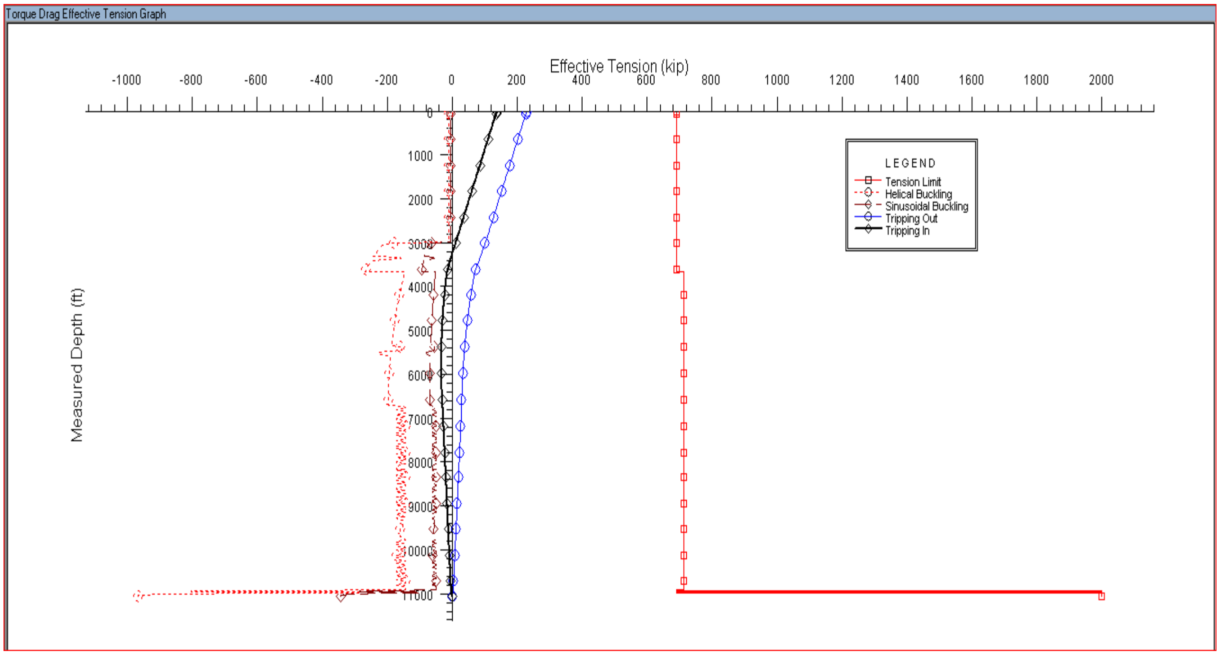


Fig.4.21: ABMO-1 ERD Well Effective Tension during Tripping in with 3650ft HWDP (Wellplan).

Figure below shows the effective tension acting along all the sections of the drillstring during rotating off and on bottom operations. For both operation modes, the effective tension curves does not cross any of the buckling load curves and hence there is no possibility to buckle the drillstring.

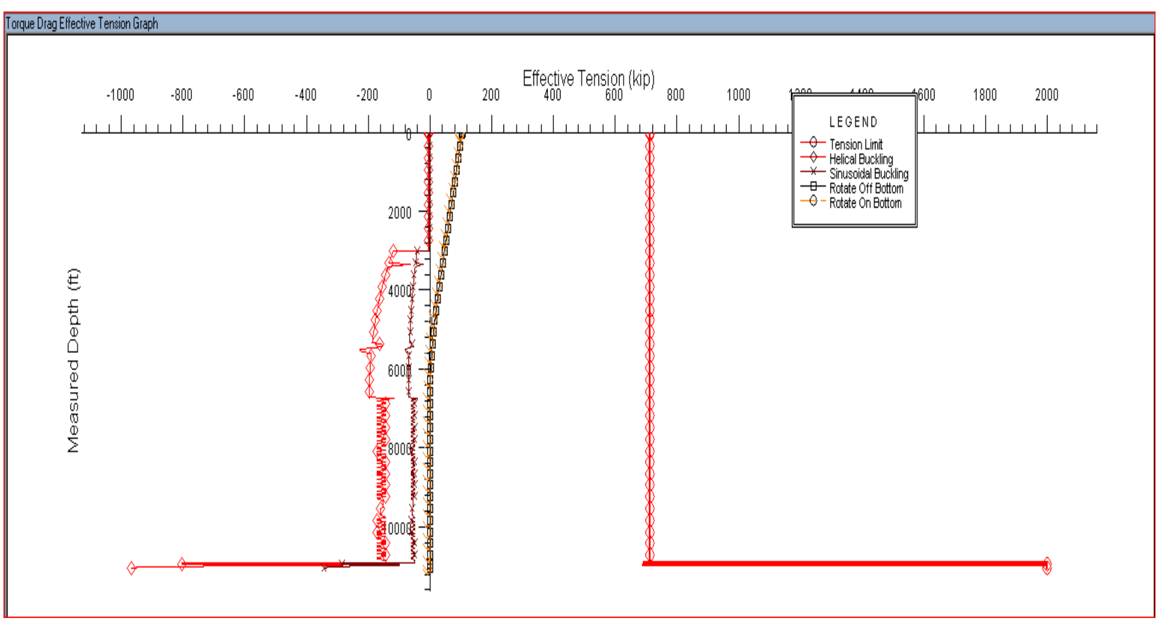


Fig.4.22: ABMO-1 ERD Well Effective Tension during Rotating on and off bottom (Wellplan).

4.2.2.2 Torque Plot:

As can be seen in the torque graph below, torque is displayed in all sections of the drillstring for the tripping in, tripping out, rotate on bottom, and rotate off bottom operations. It is obviously that the torque at surface during the rotating on bottom operation i.e. 14200ft-lbf is greater than that of the rotating off bottom operation i.e.11000ft-lbf.

It should be noted that the torque values during the tripping in and tripping out operations are equal to zero due to the fact that there is no rotation in the drillstring. Also since all the displayed torque curves during different operation modes do not exceed the makeup torque limit, the tool joints for the drillstring are not liable to over torque or break.

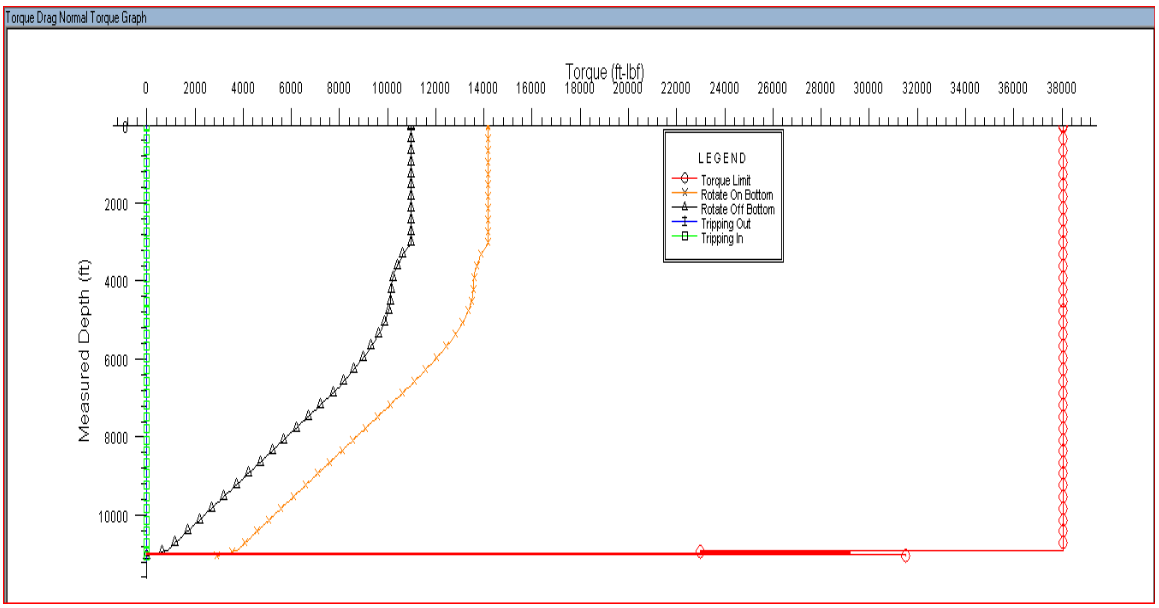


Fig.4.23: ABMO-1ERD Well Torque Plot (Wellplan).

4.2.3 Drag Chart Analysis:

4.2.3.1 Measured Weight Chart:

The figure below shows the calculated weights using Wellplan software during the tripping in and tripping out operation modes. It is clear that the weights during the tripping out operations are larger than those during the tripping operations. The figure also shows that the drillstring during tripping in operation at 11000ft bit depth will start to buckle according to helical buckling mode.

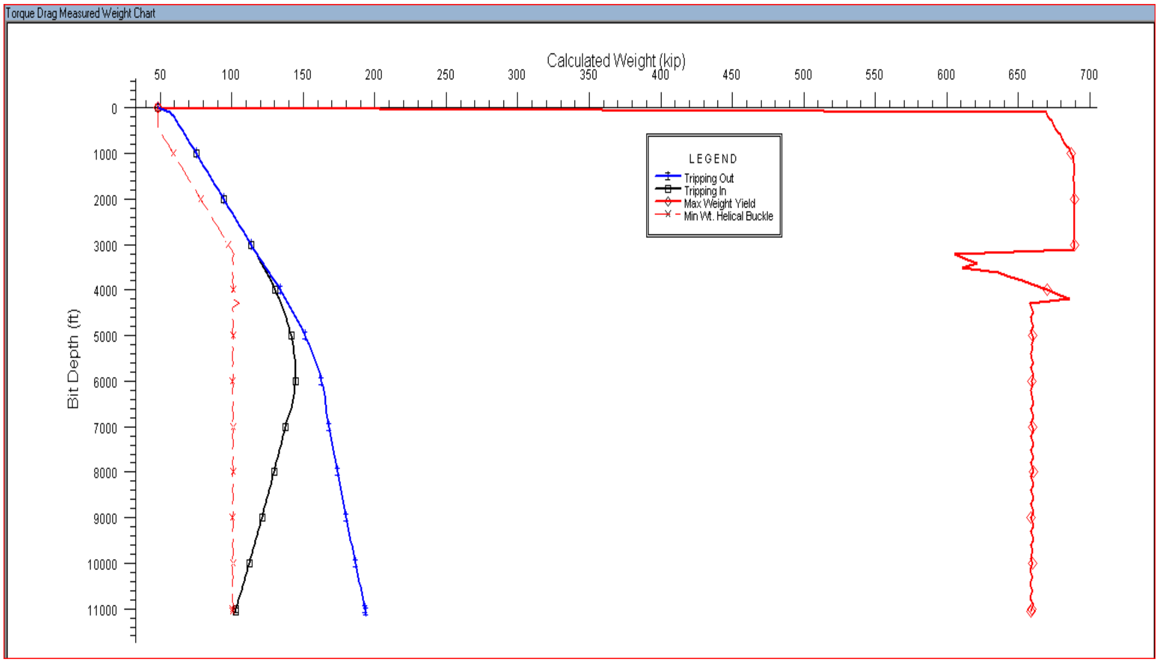


Fig.4.24: ABMO-1 ERD Well Calculated Weights during Tripping in and Tripping out (Wellplan).

With reference to the figure below, it is obvious that the calculated weights during rotating off and on bottom operations differ from each other by a constant amount approximately equals to 10 kip. The difference between these two weights normally gives the WOB. Since the calculated weights do not cross the minimum weight to helical buckling or maximum weight yield curves, then the drillstring will not subject to buckling during these operations along the entire well.

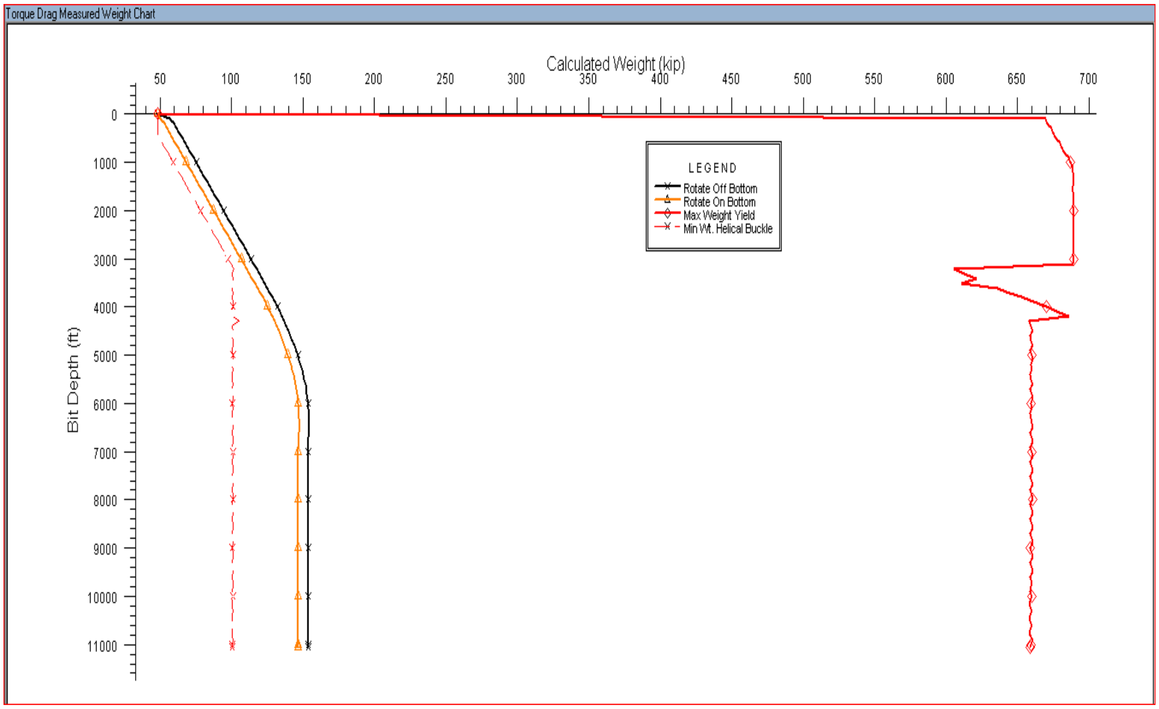


Fig.4.25: ABMO-1 ERD Well Calculated Weights during Rotating on and off bottom (Wellplan).

4.2.3.2 Torque Point Chart:

As displayed in fig.4.26 below, it is obvious that the torque at depth increases as the bit depth increases. Torque when the bit at 2000ft is equal to 0ft-lbf and 2850ft-lbf for rotating off bottom and on bottom operation modes respectively and continue to increase with depth until reach the maximum values of 10400ft-lbf and 13200ft-lbf for rotating off bottom and rotating on bottom respectively.

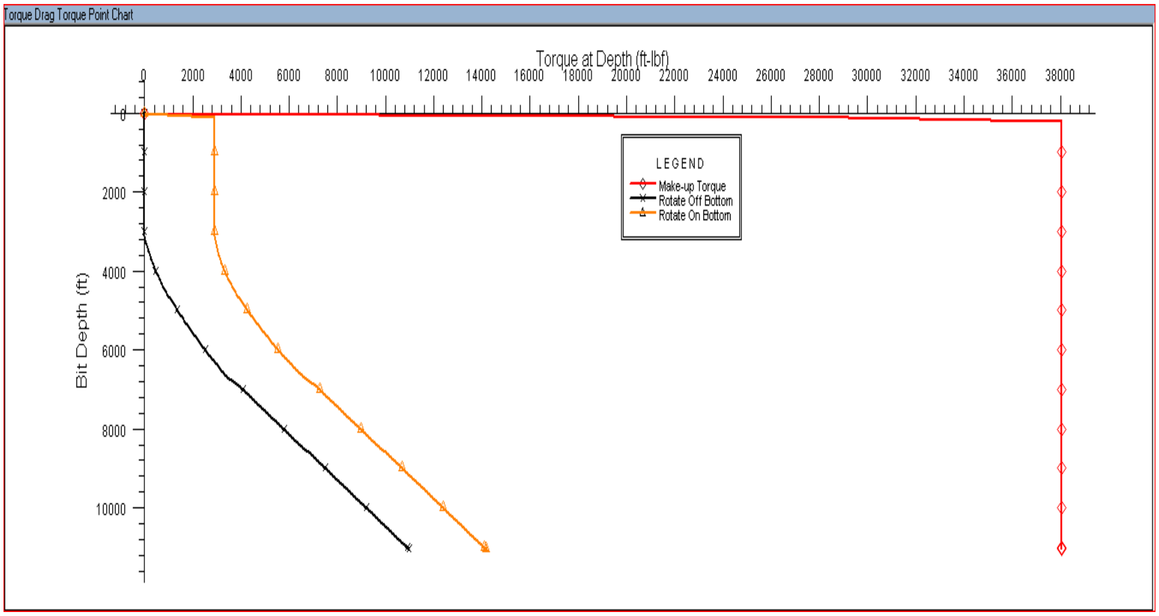


Fig.4.26: ABMO-1 ERD Well Torque Point Chart (Wellplan).

4.2.3.3 Minimum Weight on Bit Chart:

Minimum WOB to initiate helical or sinusoidal buckling can be seen in figure below. During the drilling of the ABMO-1 ERD well, extreme care should be developed to ensure that the WOB kept less than the values displayed in this figure at the corresponding bit depths. Once the WOB exceeds the minimum WOB at the corresponding bit depths, the drillstring will start buckling according to the corresponding buckling mode.

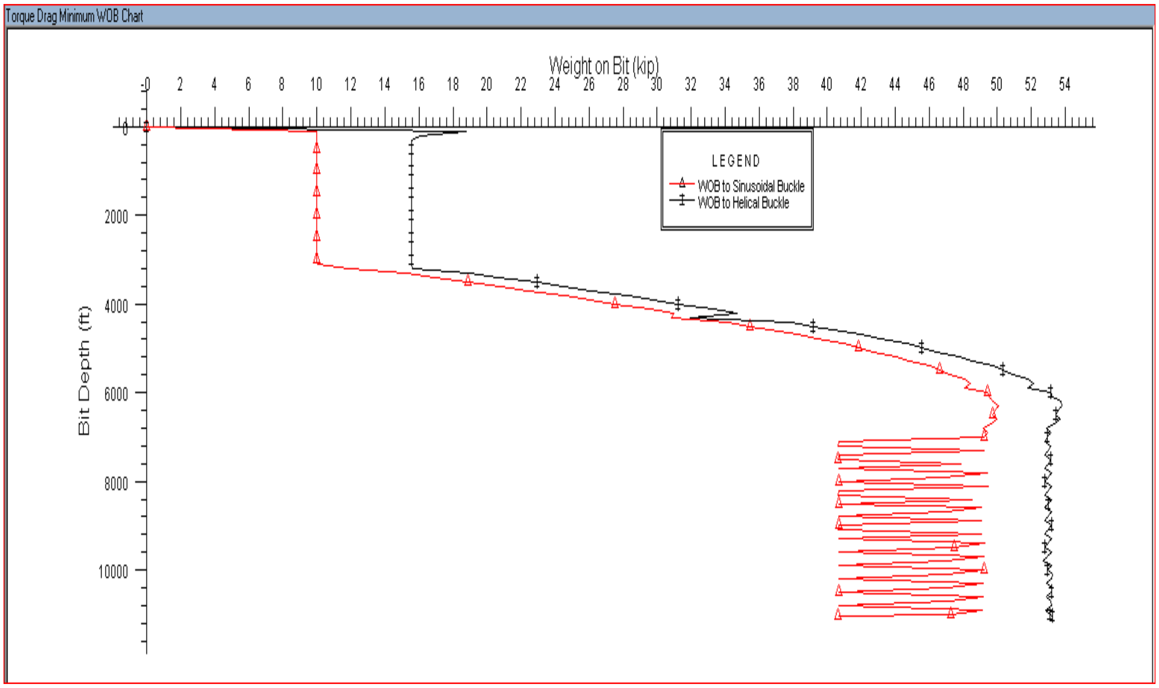


Fig.4.27: ABMO-1 ERD Well Minimum WOB Chart (Wellplan).

Chapter Five

Conclusion and Recommendations

5.1 Conclusion:

Based on the modeled and evaluated results in this project, the following conclusions can be drawn:

- T&D are key factors in the planning and drilling of the ERD wells. The principles of planning are making T&D as small as possible.
- ERD wells are unique. Special rig configurations and drilling equipment are necessary to successfully achieve ERD objectives.
- T&D analysis enables better projection for drilling facility preparation and T&D reduction action.
- Drillstring T&D are primarily caused by simple sliding friction between the drillstring and the wall of the hole.
- T&D should be analyzed by distinct openhole and cased hole friction factors and should be derived from actual field data.
- T&D calculations, together with measurements of torque and hookload, may be used to monitor hole conditions, detect drilling problems, and prevent stuck pipe.
- The cased hole friction factor in this project is matched against actual field data during different operating modes. But the openhole friction factor is assumed due to lack of accurate and actual field data.
- In normal analysis mode, the effective tension plot for ABMO-1 horizontal well does not show any possibility of buckling during all the operating modes which is not the case for ABMO-1 ERD well in which the buckling occurs during tripping in operation. This effect can be prevented by replacing the first 3650ft of drillpipe with HWDP . Also, the torque graphs show that the maximum torque in the string is at the surface which starts to decline with depth due to friction forces between the drillstring and wall of the well.
- In drag chart analysis mode for ABMO-1 horizontal well, the measured weight chart during different operating modes is established. The measured weights during tripping

in and rotate off bottom operations are considered to have a relatively good matching with the actual weights during tripping in and rotate off bottom operating modes. This is not the case for tripping out operation where the difference between measured and calculated weights is relatively large, this may be due to inaccuracy in measurements of tripping out weights.

- In drag chart analysis for ABMO-1 ERD well, there is a possibility of drillstring buckling at 11000ft during the tripping in operation thus, extreme care should be developed to minimize or even better prevent this situation. Also, the figure shows the maximum calculated weight during each of the different operation modes. The maximum weight is found to be about 190 kip during tripping out at 11000ft.
- Minimum WOB charts for ABMO-1 horizontal and ABMO-1 ERD wells are very effective tools to know the minimum weight on bit at which the drillstring starts to buckle according to the corresponding buckling mode and thus prevent these weights from occurring.
- For ABMO-1 ERD well, the maximum torques are encountered during the rotating off and on bottom operating modes to be 11000ft-lbf and 14200ft-lbf respectively.
- Drillability of ABMO-1 ERD well is determined by the mechanical limits in T&D analysis. One of these mechanical limits is due to drillstring limitations such as maximum torque due to make up torque or when failure occurs. This effect is investigated during all operating modes, the results shows that there is no possibility of drillstring buckling along the entire length of the drillstring during tripping out, rotating on bottom, and rotating off bottom operating modes. The problems are encountered during tripping in operations at 2800ft to 3200ft where drillstring buckling occurs. As mentioned, this effect can be prevented by reducing the friction in the well by use of either heavier mud or to replace the first 3650ft of drillpipe with HWDP.

  The second mechanical limit is the maximum torque available at the rig top drive system (TDS). From torque graphs, the maximum torques at surface appear to be 14200ft-lbf. It should be noted that the rig Y which is used to drill ABMO-1 horizontal well has a torque limit of about 30000ft-lbf available at the rig Y top drive system. This means that the maximum torques to be expected during drilling of ABMO-1 ERD well fall within the capability of rig Y top drive system.

The third mechanical limit is the maximum hookload that could be provided by the rig hoisting system. With referencing to the ABMO-1 ERD well calculated weight charts, it is clear that the maximum weight to be expected is found to be about 190 kip during tripping out at 11000ft. It should be noted that rig Y which is used to drill ABMO-1 horizontal well has a maximum hookload of about 550 kip. That is simply means that the maximum weights to be expected during drilling of ABMO-1 ERD well fall within the capability of rig Y hoisting system.

5.2 Recommendations:

1- It is generally agreed that ERW is equivalent to a number of vertical wells thus, ERW results in a few or minor surface footprints compared to that result from vertical well which in turn lead to a relatively clean well site. In Sudan, most of oil fields are located in areas where people graze their cattle, thereby, application of ERD technology in these areas would lead to a few number of wells and hence, a minor negative surface footprints which benefits people who live in these areas and their wild animals.

2- If the well analyzed in this project, ABMO-1 horizontal well, completed or extended in the horizontal section in reality, then, it is highly recommended that the results of this project be taken into account.

3- Also, the results of this project would provide a benchmark that could be useful if matched with the actual situation to know if the model match the plan. This will in turn helps to predict and hence, prevent the problems that might occur during the drilling of this well.

4- It is highly recommended that the actual T&D data encountered during drilling of a well to be recorded or measured with high degree of accuracy to get the best matching results.

5- It should be noted that the procedures by which students get the data required for their projects are complex and take a long period of time. Thereby, it is recommended to change the current situation to benefit both: students and scientific research efforts.

References:

1- Payne, M.L., Cxiing, D.A., and Hatch, A.j., "Critical Technologies for Success in Extended Reach Drilling", SPE 28293, *SPE Annual Technical Conference and Exhibition*. New Orleans, 25-28 September 1994. Reprinted as SPE 30140 Brief by editorial selection, JPT, Feb. 1995.

2- Aarrestad, T.V., "Effect of Steerable BHA on Drag and Torque in Wells", SPE 20929, *Europec 90*. The Hague, Netherlands, 22-24 October 1990.

3- Johancsik, C.A., Friesen, D.B. and Dawson. R., "Torque and Drag in Directional Wells – Prediction and Measurement", IADC/SPE 11380, *IADC/SPE Drilling Conference*. New Orleans, February 1983.

4- Payne, M.L., and Abbassian, F., "Advanced Torque and Drag Considerations in Extended-Reach Wells", SPE 35102, *SPE Drilling Conference*. New Orleans, LA, March 12-151996.

5- Shanzhou, M., Genlu, H., Jianguo, Z., and Zhiyong, H., "Study on Design of Extended Reach Well Trajectory", SPE 50900, *SPE International Conference and Exhibition*. Beijing, China, 2-6 November 1998.

6- Aarrestad T. V, and Blikra H., "Torque and Drag – Two Factors in Extended Reach Drilling", SPE 27491, *IADC/SPE Drilling Conference*. Dallas, February 15-18 1994.

7- Schamp, J.H., Estes, B.L., and Keller, S.R., "Torque Reduction Techniques in ERD Wells", *IADC/SPE 98969, IADC/SPE Conference*. Miami, Florida, 21 – 23 February 2006.

8- Boonsri, K., "Torque Simulation in The well Planning Process", *SPE 170500, IADC/SPE Asia Pacific Drilling technology Conference*. Bangkok, Thailand, 25-27 August 2014.

9- Mirhaj, S.A., Fazaelizadeh, M., Kaarstad, E., Aadnoy, B.S., "New Aspects of Torque and Drag Modelling in Extended Reach Wells", SPE 135719, *SPE Annual Technical Conference and Exhibition*. Florence, Italy, September 2010.

10- Mccormick, J.E., Frilot, M., Chiu, T., “Torque and Drag Model Comparison: Impact on application and Calibration of Field Data”, SPE 143623, *Brasil Offshore Conference and Exhibition*. Macae, Brazil, 14-17 June 2011.

11- Ho. H., “An Improved Modelling program for Computing the Torque and Drag in directional and Deep Dells”, SPE 18047, *63rd Annual Technical Conference and Exhibition*. Housten, TX, 2-5 October 1988.

12- Agbaji, A.L., “Optimizing the Planning, Design and Drilling of Extended Reach and Complex wells”, SPE 149099, *SPE/DGS Saudi Arabia Technical Symposium and Exhibition*. Al-khobar, Saudi Arabia, 15-18 May 2011.

13- Agbaji, A.L., 2009. *Development of An Algorithm to Analyze the Interrelationship among Five elements Involved in the planning, Design, and drilling of Extended Reach Wells*. M.Sc. The Pennsylvania State University.

14- Frafjord, C., 2013. *Friction Factor Model and Interpretation of Real time Data*. M.Sc. Norwegian University of Science and Technology.

15- Bakki, O., 2012. *A Study in Limiting Factors for Extended Reach Drilling of Highly Deviated Wells in Deep Waters*. M.Sc. Norwegian University of Science and Technology.

16- Borinb. R., 2012. *The use of alternative materials for drill pipe to extend drilling reach in shallow reservoirs*. M.Sc. University of Stavenger.

17- Bue, C., 2013, *Optimal Drilling and Completion of Deep ERD Wells*. M.Sc. Norwegian University of Science and Technology.

18- BP, 1996. *Extended Reach Drilling Guidelines*. Chester: P.L.C.

19- Halliburton, 2001. Wellplan (2000). [Computer Program] Landmark Graphics Corporation.

20- Halliburton, 1996. Compass (1996). [Computer Program] Landmark Graphics Corporation.

Appendix A: Standard Survey Report

AHTASA

Standard Survey Report

Company: GNPOC
Field: X
Site: ABMO-1 ERD Well
Well: ABMO-1 ERD Well
Wellpath: ERD Well

Date: 10/13/2015 **Time:** 13:43:06 **Page:** 1
Co-ordinate(NE) Reference: Site: ABMO-1 ERD Well, Grid North
Vertical (TVD) Reference: SITE 1338.2 above Mean Sea Level
Section (VS) Reference: Slot (0.0E,0.0N,5.8Azi)
Survey Calculation Method: Minimum Curvature

Field: X
Block 2B
Heglieg

Map Projection & Zone: Universal Transverse Mercator
UTM Zone 35, North 24E to 30E

Ellipsoid: WGS 1984

Field Datum: Mean Sea Level

Local Coordinate Reference: Site Centre
Location of Field Centre: N/A
Field Centre Map Easting: m
Field Centre Map Northing: m
Direction of Local North: Grid

Local Vertical Reference: Wellpath Datum

Geomagnetic Model: WMM_95

Site: ABMO-1 ERD Well
X
Block 2B

Site Centre: 765417.40 m **E** 9 57 27.998 N **Latitude**
1101714.20 m **N** 29 25 14.869 E **Longitude**

Site Water Depth: 0.0 ft

Magnetic Declination: 2.50 deg
Grid Convergence: 0.42 deg

Measured Depths Referenced To: SITE 1338.2 ft **above** Mean Sea Level

---

Well: ABMO-1 ERD Well
ERD Well

Originating From: 0.0 ft **+N/-S** **Map Easting :** 765417.40 m
0.0 ft **+E/-W** **Map Northing:** 1101714.20 m

Wellpath: ERD Well

Origin of Vertical Section: Slot 0.0 ft **+N/-S**
0.0 ft **+E/-W**

Direction of Vertical Section: 5.78 deg

Survey: ABMO-1 Well
Horizontal Well

Start Date: 9/18/2015

Company: GNPOC
Tool: SLB_MWD-ST

Engineer: ABMO-1

Survey: ABMO-1 Well

MD ft	Incl deg	Azim deg	TVD ft	+N/-S ft	+E/-W ft	VS ft	DLS d/100ft	Build d/100ft	Turn d/100ft	Tool/Comment
0.0	0.00	5.20	0.0	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
98.4	0.00	5.20	98.4	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
196.8	0.00	5.20	196.8	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
295.2	0.00	5.20	295.2	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
393.6	0.00	5.20	393.6	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
492.0	0.00	5.20	492.0	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
590.4	0.00	5.20	590.4	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
688.8	0.00	5.20	688.8	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
787.2	0.00	5.20	787.2	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
885.6	0.00	5.20	885.6	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
984.0	0.00	5.20	984.0	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
1082.4	0.00	5.20	1082.4	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
1180.8	0.00	5.20	1180.8	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
1279.2	0.00	5.20	1279.2	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
1377.6	0.00	5.20	1377.6	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
1476.0	0.00	5.20	1476.0	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
1574.4	0.00	5.20	1574.4	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
1672.8	0.00	5.20	1672.8	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
1771.2	0.00	5.20	1771.2	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
1869.6	0.00	5.20	1869.6	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
1968.0	0.00	5.20	1968.0	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
2066.4	0.00	5.20	2066.4	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
2164.8	0.00	5.20	2164.8	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST

AHTASA

Standard Survey Report

Company:	GNPOC	**Date:** 9/20/2015 **Time:** 23:21:05	**Page:** 2
Field:	X	**Co-ordinate(NE) Reference:**	Site: ABMO-1 ERD Well, Grid North
Site:	ABMO-1 ERD Well	**Vertical (TVD) Reference:**	SITE 1338.2 above Mean Sea Level
Well:	ABMO-1 ERD Well	**Section (VS) Reference:**	Slot (0.0E,0.0N,5.8Azi)
Wellpath:	ERD Well	**Survey Calculation Method:**	Minimum Curvature

Survey: ABMO-1 Well

MD ft	Incl deg	Azim deg	TVD ft	+N/-S ft	+E/-W ft	VS ft	DLS d/100ft	Build d/100ft	Turn d/100ft	Tool/Comment
2263.2	0.00	5.20	2263.2	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
2361.6	0.00	5.20	2361.6	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
2460.0	0.00	5.20	2460.0	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
2558.4	0.00	5.20	2558.4	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
2656.8	0.00	5.20	2656.8	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
2755.2	0.00	5.20	2755.2	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
2853.6	0.00	5.20	2853.6	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
2952.0	0.00	5.20	2952.0	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
3050.4	0.00	5.20	3050.4	0.0	0.0	0.0	0.00	0.00	0.00	SLB_MWD-ST
3148.8	2.40	5.20	3148.8	2.1	0.2	2.1	2.44	2.44	0.00	SLB_MWD-ST
3247.2	4.80	5.20	3247.0	8.2	0.7	8.2	2.44	2.44	0.00	SLB_MWD-ST
3345.6	7.20	5.20	3344.8	18.4	1.7	18.5	2.44	2.44	0.00	SLB_MWD-ST
3386.5	8.20	5.20	3385.4	23.9	2.2	24.0	2.44	2.44	0.00	SLB_MWD-ST
3415.7	8.20	5.21	3414.2	28.0	2.6	28.2	0.00	0.00	0.03	SLB_MWD-ST
3444.0	8.89	5.21	3442.2	32.2	2.9	32.4	2.43	2.43	0.00	SLB_MWD-ST
3542.4	11.29	5.22	3539.1	49.4	4.5	49.6	2.44	2.44	0.01	SLB_MWD-ST
3640.8	13.69	5.22	3635.2	70.6	6.4	70.9	2.44	2.44	0.00	SLB_MWD-ST
3739.2	16.09	5.23	3730.3	95.8	8.7	96.2	2.44	2.44	0.01	SLB_MWD-ST
3837.6	18.49	5.23	3824.2	124.9	11.4	125.4	2.44	2.44	0.00	SLB_MWD-ST
3936.0	20.89	5.23	3916.9	157.9	14.4	158.6	2.44	2.44	0.00	SLB_MWD-ST
4034.4	23.29	5.23	4008.0	194.8	17.8	195.6	2.44	2.44	0.00	SLB_MWD-ST
4132.8	25.69	5.24	4097.6	235.4	21.5	236.3	2.44	2.44	0.01	SLB_MWD-ST
4231.2	28.09	5.24	4185.3	279.7	25.6	280.8	2.44	2.44	0.00	SLB_MWD-ST
4329.6	30.49	5.24	4271.1	327.6	30.0	329.0	2.44	2.44	0.00	SLB_MWD-ST
4428.0	32.89	5.24	4354.9	379.1	34.7	380.7	2.44	2.44	0.00	SLB_MWD-ST
4526.4	35.29	5.24	4436.3	434.0	39.7	435.8	2.44	2.44	0.00	SLB_MWD-ST
4624.8	37.69	5.24	4515.4	492.3	45.1	494.3	2.44	2.44	0.00	SLB_MWD-ST
4723.2	40.09	5.24	4592.0	553.8	50.7	556.1	2.44	2.44	0.00	SLB_MWD-ST
4821.6	42.49	5.24	4666.0	618.5	56.7	621.0	2.44	2.44	0.00	SLB_MWD-ST
4920.0	44.89	5.24	4737.1	686.1	62.9	689.0	2.44	2.44	0.00	SLB_MWD-ST
5018.4	47.29	5.24	4805.3	756.7	69.3	759.9	2.44	2.44	0.00	SLB_MWD-ST
5116.8	49.69	5.24	4870.6	830.1	76.1	833.5	2.44	2.44	0.00	SLB_MWD-ST
5215.2	52.09	5.24	4932.6	906.1	83.0	909.9	2.44	2.44	0.00	SLB_MWD-ST
5313.6	54.49	5.25	4991.4	984.7	90.2	988.8	2.44	2.44	0.01	SLB_MWD-ST
5412.0	56.89	5.25	5046.9	1065.6	97.7	1070.0	2.44	2.44	0.00	SLB_MWD-ST
5510.4	59.29	5.25	5098.9	1148.8	105.3	1153.5	2.44	2.44	0.00	SLB_MWD-ST
5608.8	61.69	5.25	5147.4	1234.0	113.2	1239.2	2.44	2.44	0.00	SLB_MWD-ST
5707.2	64.09	5.25	5192.2	1321.3	121.2	1326.7	2.44	2.44	0.00	SLB_MWD-ST
5805.6	66.49	5.25	5233.3	1410.3	129.4	1416.1	2.44	2.44	0.00	SLB_MWD-ST
5904.0	68.89	5.25	5270.7	1500.9	137.7	1507.2	2.44	2.44	0.00	SLB_MWD-ST
6002.4	71.29	5.25	5304.2	1593.0	146.1	1599.7	2.44	2.44	0.00	SLB_MWD-ST
6100.8	73.69	5.25	5333.8	1686.5	154.7	1693.5	2.44	2.44	0.00	SLB_MWD-ST
6199.2	76.09	5.25	5359.4	1781.1	163.4	1788.5	2.44	2.44	0.00	SLB_MWD-ST
6297.6	78.49	5.25	5381.1	1876.7	172.2	1884.5	2.44	2.44	0.00	SLB_MWD-ST
6396.0	80.89	5.25	5398.7	1973.1	181.1	1981.3	2.44	2.44	0.00	SLB_MWD-ST
6494.4	83.29	5.25	5412.2	2070.1	190.0	2078.7	2.44	2.44	0.00	SLB_MWD-ST
6592.8	85.69	5.25	5421.7	2167.6	198.9	2176.6	2.44	2.44	0.00	SLB_MWD-ST
6691.2	88.09	5.25	5427.0	2265.5	207.9	2274.9	2.44	2.44	0.00	SLB_MWD-ST
6769.5	90.00	5.25	5428.3	2343.5	215.1	2353.2	2.44	2.44	0.00	SLB_MWD-ST
6789.6	90.00	5.32	5428.3	2363.4	217.0	2373.3	0.35	0.00	0.35	SLB_MWD-ST
6888.0	90.00	5.68	5428.3	2461.4	226.4	2471.7	0.37	0.00	0.37	SLB_MWD-ST
6986.4	90.00	6.03	5428.3	2559.3	236.4	2570.1	0.36	0.00	0.36	SLB_MWD-ST
7084.8	90.00	6.39	5428.3	2657.1	247.1	2668.5	0.37	0.00	0.37	SLB_MWD-ST
7183.2	90.00	6.74	5428.3	2754.8	258.3	2766.9	0.36	0.00	0.36	SLB_MWD-ST
7281.6	90.00	7.10	5428.3	2852.5	270.2	2865.2	0.37	0.00	0.37	SLB_MWD-ST
7380.0	90.00	7.45	5428.3	2950.1	282.6	2963.6	0.36	0.00	0.36	SLB_MWD-ST
7478.4	90.00	7.81	5428.3	3047.7	295.7	3061.9	0.37	0.00	0.37	SLB_MWD-ST
7576.8	90.00	8.16	5428.3	3145.1	309.4	3160.3	0.36	0.00	0.36	SLB_MWD-ST

AHTASA
Standard Survey Report

Company: GNPOC		**Date:** 10/13/2015 **Time:** 13:43:06	**Page:** 3
Field: X		**Co-ordinate(NE) Reference:**	Site: ABMO-1 ERD Well, Grid North
Site: ABMO-1 ERD Well		**Vertical (TVD) Reference:**	SITE 1338.2 above Mean Sea Level
Well: ABMO-1 ERD Well		**Section (VS) Reference:**	Slot (0.0E,0.0N,5.8Azi)
Wellpath: ERD Well		**Survey Calculation Method:**	Minimum Curvature

Survey: ABMO-1 Well

MD ft	Incl deg	Azim deg	TVD ft	+N/-S ft	+E/-W ft	VS ft	DLS d/100ft	Build d/100ft	Turn d/100ft	Tool/Comment
7675.2	90.00	8.52	5428.3	3242.5	323.6	3258.6	0.37	0.00	0.37	SLB_MWD-ST
7768.3	90.00	8.86	5428.3	3334.5	337.7	3351.6	0.37	0.00	0.37	SLB_MWD-ST
7773.6	90.00	8.87	5428.3	3339.7	338.5	3356.8	0.19	0.00	0.19	SLB_MWD-ST
7872.0	90.00	9.23	5428.3	3436.9	354.0	3455.1	0.37	0.00	0.37	SLB_MWD-ST
7970.4	90.00	9.58	5428.3	3534.0	370.1	3553.3	0.36	0.00	0.36	SLB_MWD-ST
8068.8	90.00	9.94	5428.3	3631.0	386.8	3651.5	0.37	0.00	0.37	SLB_MWD-ST
8167.2	90.00	10.29	5428.3	3727.8	404.0	3749.6	0.36	0.00	0.36	SLB_MWD-ST
8265.6	90.00	10.65	5428.3	3824.6	421.9	3847.6	0.37	0.00	0.37	SLB_MWD-ST
8364.0	90.00	11.00	5428.3	3921.2	440.4	3945.7	0.36	0.00	0.36	SLB_MWD-ST
8462.4	90.00	11.36	5428.3	4017.8	459.5	4043.6	0.37	0.00	0.37	SLB_MWD-ST
8560.8	90.00	11.71	5428.3	4114.2	479.2	4141.5	0.36	0.00	0.36	SLB_MWD-ST
8659.2	90.00	12.07	5428.3	4210.5	499.4	4239.4	0.37	0.00	0.37	SLB_MWD-ST
8757.6	90.00	12.42	5428.3	4306.6	520.3	4337.1	0.36	0.00	0.36	SLB_MWD-ST
8856.0	90.00	12.78	5428.3	4402.7	541.8	4434.8	0.37	0.00	0.37	SLB_MWD-ST
8954.4	90.00	13.13	5428.3	4498.6	563.8	4532.5	0.36	0.00	0.36	SLB_MWD-ST
9052.8	90.00	13.49	5428.3	4594.3	586.5	4630.0	0.37	0.00	0.37	SLB_MWD-ST
9151.2	90.00	13.84	5428.3	4689.9	609.7	4727.5	0.36	0.00	0.36	SLB_MWD-ST
9249.6	90.00	14.20	5428.3	4785.4	633.6	4824.9	0.37	0.00	0.37	SLB_MWD-ST
9348.0	90.00	14.55	5428.3	4880.7	658.0	4922.2	0.36	0.00	0.36	SLB_MWD-ST
9446.4	90.00	14.91	5428.3	4975.9	683.0	5019.4	0.37	0.00	0.37	SLB_MWD-ST
9544.8	90.00	15.26	5428.3	5070.9	708.6	5116.5	0.36	0.00	0.36	SLB_MWD-ST
9643.2	90.00	15.62	5428.3	5165.7	734.8	5213.5	0.37	0.00	0.37	SLB_MWD-ST
9741.6	90.00	15.97	5428.3	5260.4	761.6	5310.4	0.36	0.00	0.36	SLB_MWD-ST
9840.0	90.00	16.33	5428.3	5354.9	789.0	5407.2	0.37	0.00	0.37	SLB_MWD-ST
9938.4	90.00	16.68	5428.3	5449.3	816.9	5503.9	0.36	0.00	0.36	SLB_MWD-ST
10036.8	90.00	17.04	5428.3	5543.5	845.5	5600.4	0.37	0.00	0.37	SLB_MWD-ST
10135.2	90.00	17.39	5428.3	5637.5	874.6	5696.9	0.36	0.00	0.36	SLB_MWD-ST
10233.6	90.00	17.74	5428.3	5731.3	904.3	5793.2	0.36	0.00	0.36	SLB_MWD-ST
10332.0	90.00	18.10	5428.3	5824.9	934.6	5889.4	0.37	0.00	0.37	SLB_MWD-ST
10430.4	90.00	18.45	5428.3	5918.3	965.4	5985.5	0.36	0.00	0.36	SLB_MWD-ST
10528.8	90.00	18.81	5428.3	6011.6	996.9	6081.4	0.37	0.00	0.37	SLB_MWD-ST
10627.2	90.00	19.16	5428.3	6104.6	1028.9	6177.2	0.36	0.00	0.36	SLB_MWD-ST
10725.6	90.00	19.52	5428.3	6197.5	1061.5	6272.9	0.37	0.00	0.37	SLB_MWD-ST
10824.0	90.00	19.87	5428.3	6290.1	1094.6	6368.4	0.36	0.00	0.36	SLB_MWD-ST
10922.4	90.00	20.23	5428.3	6382.5	1128.3	6463.7	0.37	0.00	0.37	SLB_MWD-ST
11020.8	90.00	20.58	5428.3	6474.8	1162.7	6558.9	0.36	0.00	0.36	SLB_MWD-ST
11119.2	90.00	20.94	5428.3	6566.8	1197.5	6654.0	0.37	0.00	0.37	SLB_MWD-ST

Appendix B: Wellplan T&D Equations

1-Torque is calculated using the following equation:

$$\tau = F_N r \mu \frac{|A|}{|V|}$$

Where:

τ = Torque

F_N = Side or normal force

μ = Coefficient of friction

r = Radius of component (for collars the OD of the collar is used for drill pipe, heavy weight and casing, the OD of the tool joint is used for stabilizers the OD of the blade is used)

$$|A| = \text{Angular speed} = \text{diameter} * \pi * \frac{\text{RPM}}{60}$$

$$|V| = \text{Resultant speed} = \sqrt{(T^2)} + \sqrt{(A^2)}$$

2- Drag is calculated using the following equation:

$$F_D = F_N \mu \frac{|T|}{|V|}$$

Where:

F_D = Drag force

3- Axial force:

The T&D analysis uses two calculations for axial force. In checking for the onset of buckling, the buoyancy method is used. This is because the Critical Buckling Force calculations are based on the same assumptions regarding hydrostatic pressure. For stress calculations, the pressure area method is used.

Buoyancy method (used to determine buckling)

$$F_{axial} = \Sigma\left[LW_{air}\cos(inc) + F_{drag} + \Delta F_{area}\right] - F_{bottom} - W_{WOB} + F_{BS}$$

Pressure area method (used to calculate stress)

$$F_{axial} = \Sigma\left[LW_{air}\cos(inc) + F_{drag} + \Delta F_{area}\right] - F_{bottom} - W_{WOB}$$

Where:

L = Length of drillstring hanging below point, ft

W_{air} = Weight per foot of the drillstring in air, lb/ft

inc = Inclination, degrees

F_{bottom} = Bottom pressure force, a compression force due to fluid pressure applied over the cross sectional area of the bottom component

F_{area} = Change in force due to a change in area at junction between two components of different cross sectional areas, such as the junction between drill pipe and heavy weight or heavy weight and drill collars. If the area of the bottom component is larger the force is a tension, if the top component is larger the force is compression.

W_{WOB} = Weight on bit, lb (0 for tripping in & out)

F_{drag} = Drag force, lb

F_{BS} = Buckling Stability Force = (PressExternal * AreaExternal) – (PressInternal * AreaInternal)

Pipe:

Area External = $\pi/_4$*(0.95*BOD*BOD + 0.05*JOD*JOD)

Area Internal = $\pi/_4$*(0.95*BID*BID + 0.05*JID*JID)

Collar:

Area External = $\pi/_4$*(BOD*BOD)

Area Internal = $\pi/_4$*(BID*BID)

PressExternal = AnnulusSurfacePress + Σ (AnnulusPressGrad * TVD)

PressInternal = StringSurfacePress + Σ (StringPressGrad * TVD)

4. Additional side force due to buckling calculations:

Once buckling has occurred, there is an additional side force due to increased contact between the wellbore and the drillstring. For the soft string model, the following calculations are used to compute the additional side force. These calculations are not included in a stiff string analysis because the Stiff String model considers the additional force due to buckling in the derivation of the side force.

Sinusoidal buckling mode:

No additional side force due to buckling is added.

Helical Buckling mode:

$$F_{add} = \frac{r{F_{axial}}^2}{4EI}$$

Where:

F_{add} = Additional side force

F_{axial} = Axial compression force calculated using the buoyancy method

I = Young's modulus of elasticity

r = Radial clearance between wellbore and work string

E = Moment of Inertia.