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Application of 3-D Analytical Model for Wellbore Friction Calculation in Actual wells

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HOVEDOPPGAVE/DIPLOMA THESIS/MASTER OF SCIENCE THESIS

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Background:
A 3D analytical model is the new tool for wellbore friction calculation. Before making a final recommendation about the model as a reliable tool for using in software and industry it is required to apply it for number of case studies. The comparison of the results with actual well data and quality check with Wellplan software is the way for evaluation of the analytical model. An application of the model in the complex well with complex wellbore profiles should be also further simplified.

Task:

- Perform torque and drag calculation for selected test wells using the analytical model
- Suggest simplification of the analytical model. Create a simple torque and drag simulator
- Perform quality check using the torque and drag modules in Wellplan software
- Perform an evaluation and comparison of the analytical model with actual well data

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Studieretning/Area of specialization:	*Petroleum Engineering, Drilling Technology*
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Sigbjørn Sangesland

Preface

This document represents the Master Thesis work written during the spring semester of 2012 under Master of Science program in the department of Petroleum Engineering and Applied Geosciences at Norwegian University of Science and Technology.

I would like to thank my supervisor, Professor Sigbjørn Sangesland, for his guidance and patience during the development and writing of this thesis.

I would like to thank Johan Eck-Olsen and all the involved Statoil staff for providing me with the necessary data and information regarding to the Oseberg well.

I am very grateful to Professor Bernt Sigve Aadnøy, University of Stavanger, and Mohammad Fazaeli-zadeh, University of Calgary, for their assistance with Analytical Friction Models.

I would also like to give special thanks to Lanventiv Eqor. His guidance, help and advises has been vital to carry out this thesis.

Finally I would like to thank all my friends and family members for a great support, their love and patience.

Summary

With the increasing number of drilled ultra-extended reach wells and complex geometry wells, the drilling limitation caused by excessive torque and drag forces must be further investigated. The wellbore friction being a main limiting factor in extended reach well needs to be studied with the new developed models.

This master thesis presents an application of the new 3-dimentional analytical model developed by Bernt S. Aadnøy in the synthetic test and four real wells. Quite diverse wellbore trajectory and depth has been chosen for a better evaluation and comparison of the model with the measured data. In order to investigate the potential and limitation of the model, torque and drag analysis during the different operations such as tripping in, tripping out, rotating off bottom, combined up/down were investigated.

An application of the analytical model for wellbore friction analysis in the actual wells is very time consuming and requires a lot data/input manipulation. As a part of the thesis assignment, it was required to create simplified means for application and testing the analytical model. With visual basic application in Excel a simple torque and drag simulator was created purely based on the analytical model simple solution. Along with the analytical model the master thesis includes Wellplan software for torque and drag analysis in all the included test and actual wells. Along with this, the project has a brief literature study of 3D analytical model and torque and drag concept in general.

The analytical model gives a reasonable torque and drag results. Based on comparison between the model and actual measurement, it has been observed that the analytical model simple solution in some cases may not precisely describe wellbore friction analysis. The discrepancy between Wellplan and the analytical model prediction occurs during the tripping in operations. Being a strong function of tension/compression in the drill string the analytical model for more accurate torque and drag prediction requires an application of the complete solution. The main challenge for this model is the complexity of its full application. There is an uncertainty regarding the model application in conjunction with drillstring effective tension. For the actual well application it is time consuming and requires drillstring effective tension analyzing which make the model disable for the real time analysis.

The analytical model must be further investigated by application in the real well with good quality of measured data.

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Introduction

Due to the complex wellbore profiles and involved field operations in most of the currently drilled wells, it is required to have a good model for wellbore friction analysis. The model must be a reliable tool to be able to give a precisely torque and drag analysis during planning, drilling and post-operational phases. During the planning phase the models are used to optimize the trajectory design to minimize the torque, drag and contact forces between drillstring and borehole wall. The discrepancy between torque and drag prediction and actual measurements in conventional wells is within 20%. While for the Extended Reach Drilling (ERD), Horizontal or Multilateral Drilling, Ultra-Deep Drilling and 3D wells this value may significantly increase[16]. Accurate torque and drag analysis gives an opportunity to build reliable well trajectory taking into account capabilities of the rig and geological complexity. Ideally the model must predict realistic forces, bending moment and contact loads along the wellbore. Along with the precise results obtained for torque and analysis the model shall also be easily applicable.

Currently, there are three most widely used models for wellbore friction calculation. The first model is Johancsik model which is still used in the torque and drag simulators in the industry. The second one is modified Texas A&M model. This model used to be a 2-D model which has been modified into 3-D model in order to be applicable for side bends as well as build-up and drop-off sections. The third model is a new analytic fully 3-dimentional torque and drag model was developed by Aadnøy, Fazaeli and Hareland[21]. All abovementioned models are soft string models when the drill string assumes as a cable. As an alternative could be mention stiff string model. There have been many stiff string models developed, but there is no industry standard formulation. S. Menand introduced a new stiff string model which uses the finite element analysis when the drillstring and BHA is considered as a beam element.

The best way for the model evaluations is comparison and investigation the simulated results with the actual measurements of hook load and torque values. If there is a discrepancy between the model and actual hook load or/and torque then this may simply mean either a problem with model or this may be an indication of some well problems. In general, such comparison gives an opportunity to determine a potential and limitation of applied model. Along with this, the wellbore friction model must be tested in the wells with diverse wellbore trajectories and drilling operation before to be proved as reliable tool for the torque and drag analysis in the industry.

The analytical model does not wide-use application in an industry. S.A Mirhaj and M. Fazaelizadeh studied the analytical model by application of it in several ERD wells. The prediction results were also compared with the different wellbore friction models such as Exxon model, Modified Texas A&M. Faraelizadeh by using the analytical model, made real-time wellbore friction analysis to determine commencement of drillstring sticking during extended reach well drilling.

1. Literature Study

Torque and drag are the key aspects in the planning and operational phases of an ERD well. Each phase of the ERD well; drilling casing, completion and workover operations, must be carefully evaluated in order to be successful. A poor understanding of the torque and drag issues in ERD well is the main reason of failures in most cases.

1.1 Torque Definition

Torque is rotational force generated from number of sources within the wellbore such as mechanical torque, frictional torque, and bit torque. Along with this, drillstring dynamics or vibrations may also contribute additional torque[12].

Contact loads between the drill string and the open hole or the casing generate frictional torque. The friction torque assumes perfect hole cleaning condition and rotating off bottom operation. Current torque is the function of the following aspects:

- Tension or compression in the drillstring
- Dogleg severities
- Hole and pipe sizes
- String weight
- Inclination
- Lubricity or friction factor[12]

All these aspects must be well understood and controlled to meet operational requirements. The higher the tension or compression, the higher the contact forces between drillstring and wellbore. High dog leg severity will increase the contact forces. The dog leg severity has high effect in the drillstring length with a greater tension, i.e. in the shallow well depth. Along with this, contact forces are a function of the clearance between the drillstring and wellbore. The drillstring stiffness will be high in a small annulus and will contribute into the extra friction contact forces. In addition, having high string weight the contact force will be high due to the greater weight pushing against the side of the hole. The wellbore inclination is also a key parameter in the analysis. Higher inclinations results in a larger component of the string weight perpendicular to the borehole[12].

Torque which is generated as the result of the interaction between drillstring or BHA and unstable formation or cutting accumulation is defined as a mechanical torque. Usually this torque is difficult to predict and simulate during the planning phase. Most of the industry torque and drag simulators do not take into account the mechanical torque. This gap could be compensated by using a slight high friction factor.

1.2 Drag Definition

Drag is an axial force which is generated only when the pipe is moved in an axial direction without rotation. It always has an opposite direction to that in which the pipe is moved[12].During tripping in and out operations, when the drillstring is not rotated, the drag forces are higher. While, when the drillstring is rotated the drag forces are reduced[14].

During the field operation we are particular interested in the measurements of the following parameters:

- Rotating of bottom weight –this is the weight of the drillstring without drag added with the pipe in rotation and the plus travelling block weight.
- Pick up weight - this is weight of the drillstring during the tripping out operation.
- Slack off weight - this is weight of the drilling during the tripping in operations.
- Torque off bottom is a measure of the torque when rotating off bottom of the hole.

A real time torque and drag monitoring, gives an opportunity to obtain current down hole drilling condition and predicts upcoming situations[13].

During the planning phase of the torque and drag analysis the worst case scenario must be considered to be sure that the drillstring can be drilled, tripped in and out and rotated. Drag forces during tripping in and out operations are not liberalized reversals of one another. This happens due to the number of reasons such as wellbore geometry, drillstring geometry, the contact points which are different and which cause different friction factors.

Particular attention must be paid to casing running and pulling operation if necessary. To evaluate bucking and tension capabilities it is required to determine effective tension/compression in the drill string[18].

1.3 Wellpath Design Options and Well Section in ERD

Wellpath design in most cases can determine the success or failure of ERD well. It must be designed to avoid geological complex areas, to reach the target reservoir and to meet the drilling requirements[15].Wellpath design options have strong effect on torque, drag and buckling in ERD well. Most often in ERD wells catenary profile, S-turn profile or complex 3D well profiles are used. Each suggested wellpath design may have advantages and challenges which must be carefully considered[12].It is crucial that the chosen well path design would decrease torque, drag forces and diminish buckling chances. Proper wellpath design reduces the side forces which is important in ERD wells. Nowadays, complex 3D wells are becoming more common in the industry. Below is a possible summarized wellbore section that may be included in ERD wells:

2D-Sections

- Straight Vertical/Inclined -inclination const, azimuth “const”
- Build-up section – inclination “+”,azimuth “const”
- Drop-off section – inclination “-“,azimuth “const”
- Side Bend - inclination “const”, azimuth “-“or “+”
- Horizontal –inclination “const”, azimuth “const”

3D- Sections

- Build-up with right side bend – inclination “+”, azimuth “+”
- Build-up with left side bend – inclination “+”, azimuth “-“
- Drop-off with right side bend –inclination“-“, azimuth “+”
- Drop-off with left side bend – inclination”-“, azimuth “+”

Where signs “+”, “-“-denotes increasing and decreasing in an angle respectively, while the “const” indicated that the current angle does not change.

1.4 Soft-string vs Stiff -string Model

There are number of mathematical models which were developed to evaluate the mechanical behavior of the drillstring inside the wellbore. Each model may have its own specified theory and assumption. The soft string and the stiff string models are basically two types of models which are used for a torque and drag analysis.

The wellbore tortuosity has an effect on the surface contact between the drillstring and wellbore. The tortuosity may be defined as macro and micro tortuosity. The macro tortuosity characterizes an irregularity over the length greater than 10 meters, while the micro tortuosity is defined as the tortuosity in the wellbore in a shorter length[24].Both types of wellbore irregularities have an influence on a wellbore friction parameter, the value of which is difficult to predict and estimate during the well planning phase.

Currently, most of the industry wide used torque and drag models are based on the soft string model or often called a “cable” or “chain”. This approach assumes that the drillstring is deformed to the shape of wellbore and has continuous surface contact area between the drillstring and borehole. The model excludes the bending stiffness in the drillstring and borehole clearance. Having smooth well trajectory, the soft string model has a good approximation of forces and contact loads. However in the complex wellbore profiles with micro and macro tortuosities, the soft string model may introduce errors and cause misinterpretation of drilling problems[24].Along with this, due to the friction force generated by the rotation, the pipe has a tendency to climb on the borehole wall. It will cause that the contact force will be less than if the pipe lays on the low side of the wellbore which is the main soft string model assumption, Figure 1[16].To eliminate or reduce an error term during the soft string model application, some authors suggest a correction to the friction coefficient[16].

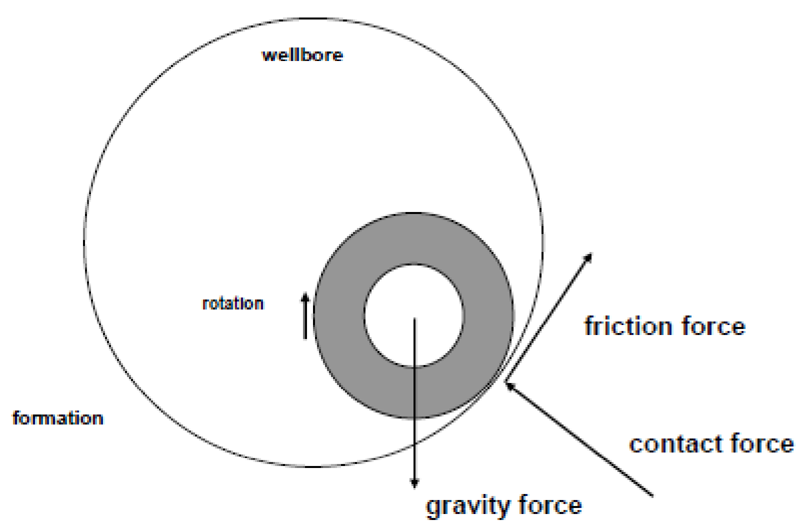

Figure 1: Drillstring Rotating Equilibrium Position[16]

And in general, the drillstring position relative to the wellbore may be on the side, high, right or left side depending on the wellbore section and drillstring operation, Figure 2. The soft string model cannot predict such diverse positing which in some cases will lead to errors in torque and drag prediction[24].

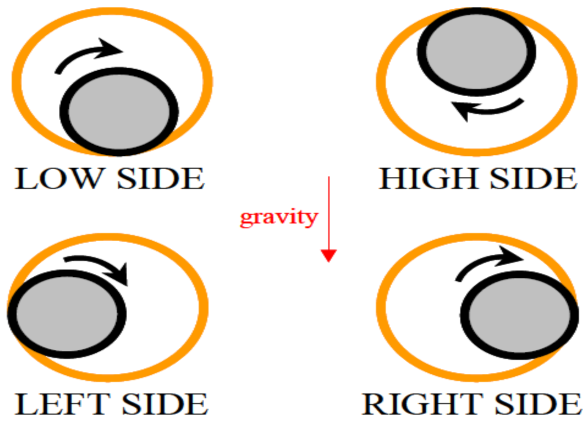

Figure 2: Drillstring position related to the borehole[24]

In addition, the soft string assumption treats left turn and right turn drillstring rotation in the same way. However the drillstring positioning and surface wall contact will be different in both cases24. The stiff sting model, which has a distinct approach in both cases, gives about 10 % difference. As it can be noticed from a model name the stiff string model takes into account drillstring stiffness in the wellbore and also the annulus clearance. Even though there have been many stiff string models developed, none of them has a standard formulation in the industry. S. Menand and his colleagues introduced rather new stiff string model which based on the 3D visualization experiments of the drillstring deformed inside the wellbore that shows more accurate results comparing with the conventional soft string model. The model includes a contact algorithm which calculates all the contact points the drillstring and the wellbore. By application of new stiff string model, the drillstring reacts naturally to the forces and moments and therefore more accurately predicts torque and drag in all shown in Figure 2 drillstring positions. The stiff string model predicts more realistically the side forces along the drillstring. This gives an opportunity to determine torque and drag losses and better match with the actual measurements[24].The main disadvantage of the stiff string model is the high time consuming required for its application. This is inappropriate for real time torque and drag monitoring.
Based on the experiments, both soft and stiff string models shows similar results over the smooth wellbore profile, and starts to give discrepancy starting in a tortuous wellbore. The soft string model has a tendency to overestimate torque and drag prediction[24].
So there are two main criteria for a model which are important to meet the industry requirements, the first is to give a valid and reasonable torque and drag prediction and second an ability to apply for real time analysis.

1.5 Friction Factor

Friction factor in ERD wells is rather vague parameter, because along with a friction, it contains a number of other aspects such as:

- Mud system lubricity
- Pipe Stiffness
- Cutting Bed
- Key seats
- Differential sticking
- Dog leg severity
- Hydraulic effect[12]

The friction factor term includes uncertainties such as tortuosity, mud properties, fluid viscous effect, cutting bed, formation instability, wellbore temperature and pressure, non-uniformed geometrical interaction between the borehole and drillstring and etc[18].

Usually wellbore tortuosity cause additional problems during the torque and drag analysis. In order to take into account the wellbore irregularities, the friction factor may be calibrated. Due to the fact that there are no industry standard for defining exact relationship between friction coefficient and wellbore tortuosity, the drag values may be either overestimated or underestimated comparing with actual measurements[18].

Due to the various factors such as cutting bed, temperature and suspended particles, the mud weight does not stay constant over the borehole. Most of the torque and drag software assume constant mud weight during the analysis, but even if they somehow are considered in the model, the local declination are still exist. This will affect on the side forces and consequently the drag forces will also be influenced. Local mud weight variation may be taken into account by correction of a friction factor over the particular wellbore intervals based on the borehole cutting transport theory. It is important that, the mud properties used during the planning phase must be the same with baseline used mud in a well. Therefore each drilling fluid types has to be specified in friction factor ranges, shown, for example, in Table 1[18].

Table 1: Range of friction factors[18]

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

In most torque and drag software, user can only apply one single friction factor for open and single friction factor for cased hole section. However, to be able to precisely model torque and drag prediction it is required to use separate friction factors for tripping in, tripping out and torque operations. The friction factor being a “fudge” parameter is dependent on the model used for the calculation. The friction back calculated for the slack off and pick up operations is usually different than the back calculated friction for a torque. The discrepancy may also be between pick up and slack off friction coefficients. This could be due to the incorrectly modeled tension/compression forces in the drillstring during these operations[24].Therefore, application of two or three friction factors in order to better match with actual measurements is required in some cases. In addition, the friction factor calibration in different software may give various values[12].

Friction factor having even slight variation in the ERD well can have a great effect on the torque and drag analysis. Therefore it is important that in the planning phase the sensitivity analysis will be included in order to ensure there is a realistic and acceptable contingency for the drilling[24]. The friction coefficient of 0.25 for open hole and for 0.2 cased hole are normal friction coefficients used in industry during the Well planning phase[11].

1.6 Torque and drag Reduction Methods

To maximize possible target reach, it is important to apply all the possible torque and drag reduction techniques. This sub-chapter briefly summarizes the torque and drag reduction methods. In order to mitigate torque and drag forces engineers have developed various means. These methods may be listed as the following:

- Wellpath design
- Lubricants
- Light weight string components
- Hole cleaning
- Co-polymer beads
- Mechanical friction reduction tools
- Increased drill string and rig capability[15]

Drag is the function of the normal force, tubular movement and coefficient of friction. The torque value is also proportional to the normal force, coefficient of friction, drillstring configuration radius and tubular movement. By reducing any of the mentioned components will lead to a reduction of a torque and drag value[15].

Efficient hole cleaning can eliminate problems with cutting accumulation and remediate high torque and drag in the ERD wells. In ERD well, hole cleaning may be quite challenging and therefore must be carefully planned for each well section. The efficient cutting removal failure could lead to a significant torque and drag increase and without successful attempts to mitigate it, to even more severe operational problems such as drillstring stuck[22].

In order to decrease normal forces in a wellbore, the high buoyancy can be beneficial as it will limit the load on the drillstring. However the disadvantage of a dense fluid is the fact that high particle size in the mud, after some concentration will increase the friction[22].Slight mud weight rise in a

wellbore section can increase friction factor up to 10%. This means that even small increase in mud column pressure can cause differential sticking.
In addition, low friction in the wellbore can also be obtained by using drilling mud additives. Figure 3shows comparison of three (Table 2) different mud additives and corresponding friction factor[13].

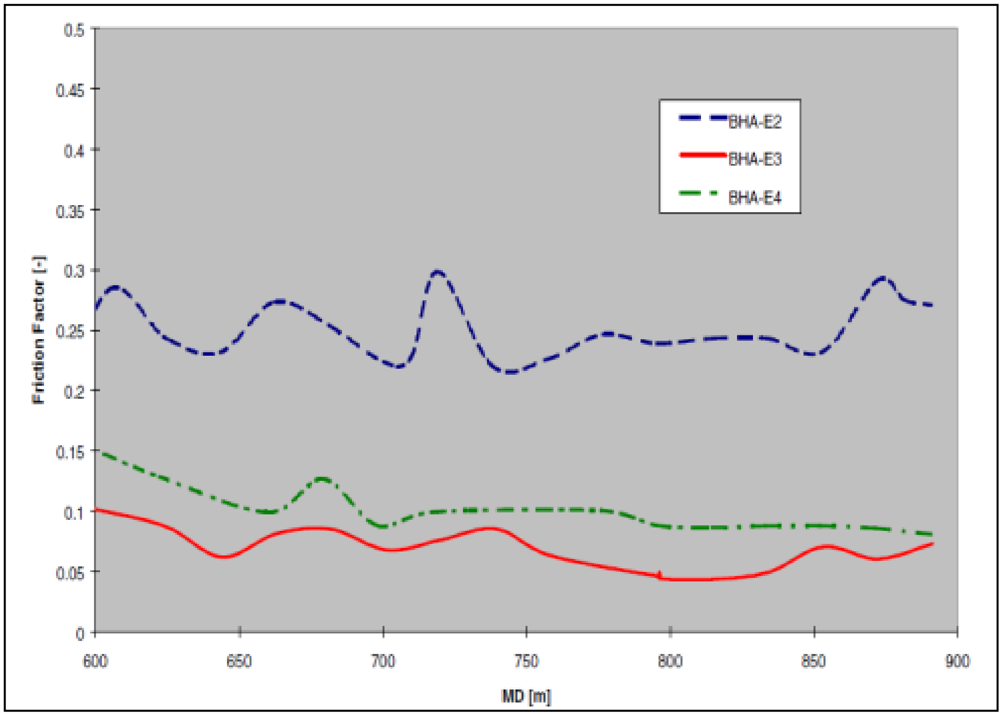

Figure 3: Three different friction factors in similar offset wells with different mud additives[13]

Table 2: Comparison of friction Factors with Different Drilling Fluids[13]

Well	BHA-E2	BHA-E3	BHA-E4
Averaged FF	0.251	0.067	0.1
Fluid Type	Fresh water/gel	Aqua-drill	Aqua-drill+5% DFE-1415
Relative FF	1	0.25	0.4

The sail angle should be designed with as high inclination as possible in order to reduce axial tension and hence friction in the curved hole sections. The tortuosity must be decreased and dog leg value should be minimized.
By using mechanical devises and lubricants for a given wellpath and borehole condition the torque and drag values could be significantly reduced. Different types of such mechanics can be installed between the connections or directly on the pipe. Most widely used in the industry are rollers and non-rotating sleeves. Presence of these components on the drillstring will assist drilling and running operations by increasing available weight and decreasing slip stick effect[18].As the general recommendation during the drilling ERD well is to use low weight drill pipe and BHA. This will reduce tension and increase buoyancy, leading to low friction[22].

1.7 The 3D Analytical Model for Wellbore Friction

Aadnøy developed a new analytical solution to calculate wellbore friction for different well geometers. The model can be applied for all the wellbore shapes such as vertical sections, build-up bends, drop-off bends and straight sections. For all these geometries the analytical model is valid for tubular both in tension and in compression[17].The model has the capability of calculating torque and drag for different models such as rotating, tripping and a combination of modes such as reaming and back reaming operations and for completion operations.[2, 3,21.]

The drillstring is modeled as a soft string. The soft sting model is so called because it neglects any tubular stiffness. This means that the pipe is behaving like a heavy cable lying along the wellbore which implies that axial tension and torque forces are supported by the string and contact forces are supported along the wellbore. In high tension the string weight is negligible as compared to the tension[21].

As the primary objection behind the new model is to introduce simplified torque and drag calculation. Torque and drag solutions for the straight section is same for all the cases. However for the curved section the equations and coefficients must be carefully considered. The authors introduced set of equations for wellbore friction calculation in a curved section which could be summarized as the simplified and the complete solution. The main criteria which must be taken into account before application of these or combination of both solutions is tension and compression values in the drillstring. The chapter summaries the main equations and approaches used in both suggested solutions.

One of the advantages of the analytical model is the fact that it includes capstan effect.The capstan effect is the normal force caused by the deformation of an axial loaded element about an obstacle. This increases the tension or compression due to the capstan effect. The capstan effect can cause a reduction in tension when tripping in and an increase in tension whenpulling out of hole. During tripping in this may be seen by reduction in weight on surface and an increase may be experienced in tension if tripping out operation.[20, 27,28.]

The entire well can be modeled by two sets of equations, one for straight wellbore section and one for curved wellbores. A curved equation is based on the absolute dogleg of the wellbore and therefore applicable for 3-dimesional wells.[2, 3,21.]

The absolute dogleg can be determined by the following equation:

$$\cos\theta = \sin\alpha_1 \sin\alpha_2 \cos(\phi_1 - \phi_2) + \cos\alpha_1 \cos\alpha_2 \quad (1)$$

Where α 1, 2 and φ 1, 2 refers to two consecutive survey measurements of inclination and azimuth respectively.

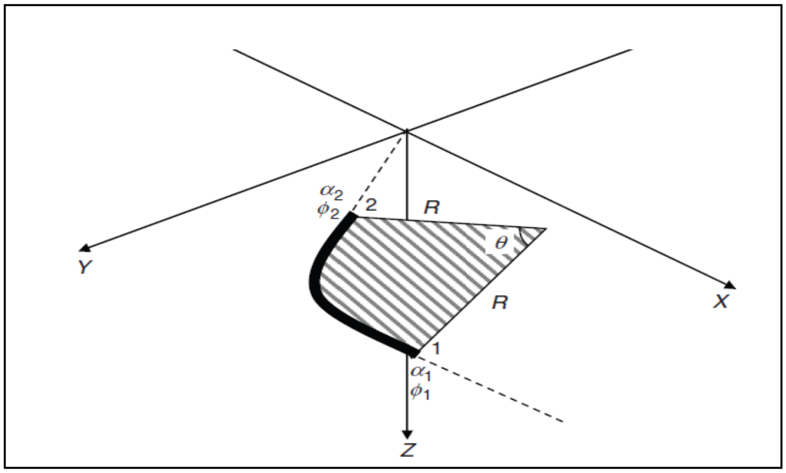

Figure 4: The dogleg in 3D space[2]

The dogleg θ is measured in an arbitrary plane (Figure 4), and it is a function of both inclination and azimuth. Therefore, the absolute dogleg is a fully 3D representation of the directional change[2].

1.7.1 Buoyancy effect

The sting tension or the effective string weight in a fluid filled well is the unit pipe weight *w* multiplying by the buoyancy factor β. The buoyancy factor is determined by the following equation:

$$\beta = 1 - \frac{\rho_o A_o - \rho_i A_i}{\rho_{pipe}(A_o - A_i)} \qquad (2)$$

Where subscript *o* refers to the outside pipe area and subscript *i* to the inside.

$$\beta = 1 - \frac{\rho_o}{\rho_{pipe}} \qquad (3)$$

The simplified buoyancy factor given in equation (3) can be used if the mud density in the annulus is equal to the mud density inside the drillpipe. Otherwise corrections must be applied.[22]

1.7.2 Drag for Straight Inclined Wellbore Sections without Pipe Rotation

A main characteristic of a straight wellbore is that pipe tension is not contributing to the normal pipe force and therefore not affecting friction. Straight sections are weight dominated due to the fact that only the normal weight component gives friction (Figure 5).

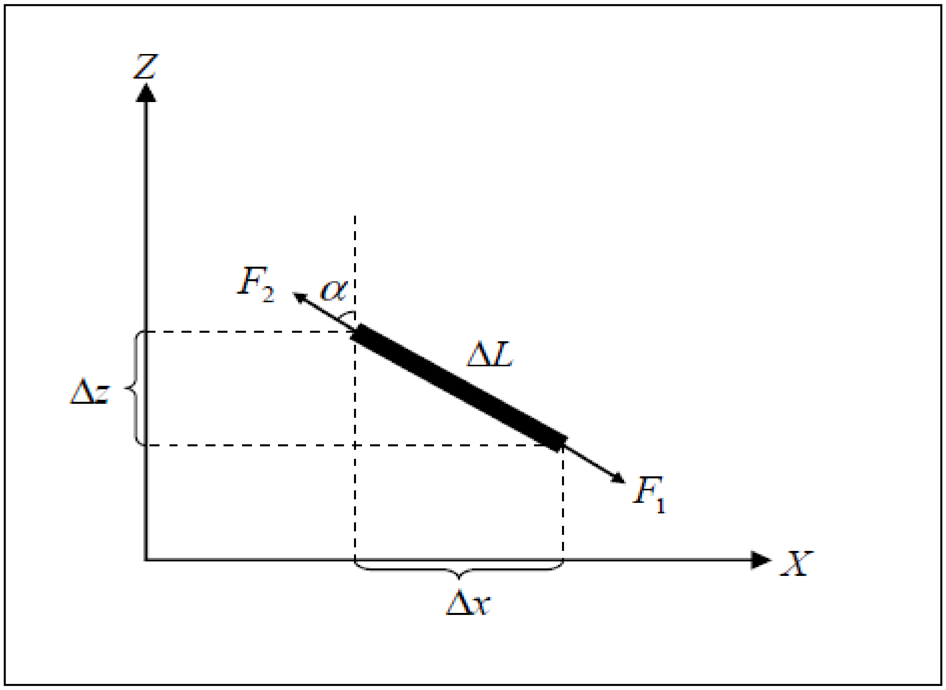

Figure 5: Pipe element along inclined straight section[2]

The top force F2 of inclined pipe is given by:

$$F_2 = F_1 + \beta \Delta L w(\cos\alpha \pm \mu \sin\alpha) \qquad (4)$$

Where sign + means hoisting and – means lowering of the pipe.

1.7.3 Torque for Straight Inclined Wellbore Sections without Pipe Motion

The torque is defined as the normal force weight component multiplied by the coefficient of friction and the pipe tool joint radius. The equation for torque is:

$$T = \mu r \beta w \Delta L \sin\alpha \qquad (5)$$

For α equal to zero in a vertical section, no torque applies, while for α equal to 90 degree in a horizontal section, the maximum torque applies.

1.7.4 The Simple Solution for Curved section

The simple solution assumes that the tension in the drill string is higher than the weight of the pipe in the curved section. It is so called tension dominated process.[2]

Drag for Curved Wellbore Sections without Pipe Rotation

For curved borehole sections, the normal contact force between string and hole is strong function of the axial pipe loading (Figure 6). This is therefore a tension dominated process. In, for example, a short bend, the tension is often much larger than the weight of the pipe inside the bend. In the equations, it is assumed that the pipe is weightless when authors compute the friction, but adds the weight at the end of the bend [2].

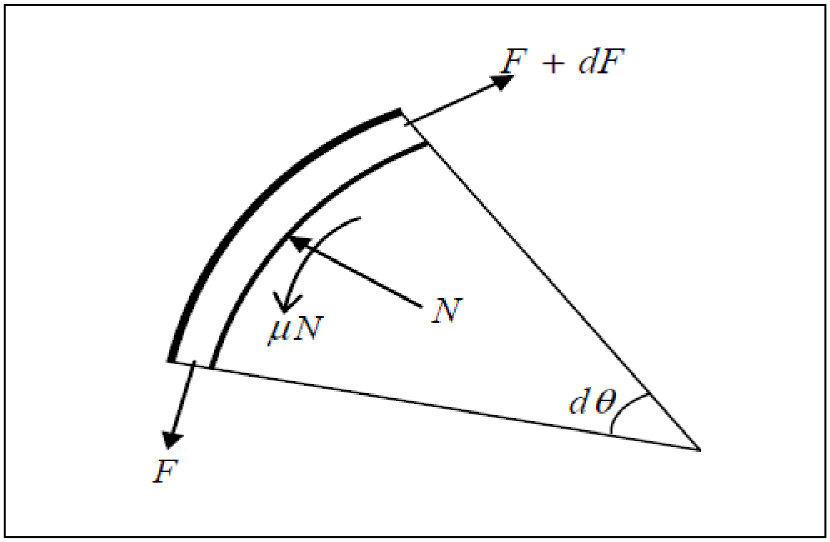

Figure 6: Pipe element along curved section[2]

$$F_2 = F_1 e^{\pm \mu |\theta_2 - \theta_1|} + \beta w \Delta L \left[\frac{\sin \alpha_2 - \sin \alpha_1}{\alpha_2 - \alpha_1} \right] \qquad (6)$$

Where sign +means hoisting and –means lowering of the pipe.

Torque for Curved Wellbore Sections without Pipe Motion

For rotating string, the same contact force applies, only friction direction is tangential. The torque for a drillstring that is not pulled or lowering is:

$$T = \mu r N = \mu r F_1 |\theta_2 - \theta_1| \qquad (7)$$

1.7.5 The Complete Solution for Curved section

In cases when the tension/compression in the drill string is not high enough over the curved section an error can occur. For example, at the very bottom of the string tension is small and the weight dominates friction also for bends. The complete solution better predicts prediction in these cases. Equation (8) is in general form for force calculation. The different solutions can be obtained by selecting the signs of the coefficient of friction and the well direction.

$$F_2 = F_1 e^{-AB\mu|\theta_2 - \theta_1|} + \frac{\beta w R_\alpha}{1 + \mu^2} (A(1 - \mu^2)(\sin \alpha_2 - \sin \alpha_1 e^{-AB\mu|\theta_2 - \theta_1|}) - 2B\mu(\cos \alpha_2 - \cos \alpha_1 e^{-AB\mu|\theta_2 - \theta_1|})) \qquad (8)$$

Table 3 shows the sign for A and B constants for the particular operations, well section and drillstring effective either tension or compression conditions.

Table 3: Sign of A and B Constants for different Geometry sections during hoisting and lowering[2]

Sign Constant	Build-up/Hoisting	Drop-off/Hoisting	Build-up/Lowering	Drop-off/Lowering
A-Tension	+	+	-	-
A-Compression	-	-	+	+
B	-	-	-	+

The comparison of the simple solution with the complete, determines the weight term K. This term could be derived as a following equation:

$$K = \frac{A(1-\mu^2)(\sin\alpha_2 - e^{-AB\mu(\alpha_2-\alpha_1)}\sin\alpha_1) - 2B\mu(\cos\alpha_2 - e^{-AB\mu(\alpha_2-\alpha_1)}\cos\alpha_1)}{(1+\mu^2)(\sin\alpha_2 - \sin\alpha_1)} \quad (9)$$

The complete solution also includes equations for calculation during the drillstring combined motion. All the complete solution equations and brief description are included in the Appendix A.

2. 3D Model Simulator

In order to evaluate the analytical model it was required to test it by application in number of actual wells. In ERD wells and wells with complex wellbore profiles, manual calculation is very time consuming and there is a high chance to make a mistake. In order to mitigate these challenges, the master thesis includes a task which requires suggestion of a simple way for the analytical model application by creating a simple torque and drag simulator.

The simulator has been created in Excel with Visual Basic application and called 3D Model. It is rather simple tool for use which gave valid results. The software is based on the analytical model theory described in the Chapter 1 and Appendix A. Due to the complexity of the complete solution it has not been included into the simulator. The software calculation for the curved section is purely based on the simple solution, which assumes that the tension in the string is much higher than the weight of the pipe in the bend.

Indented to be maximally friendly user, the simulator consists of three excel sheets: “Input Data”, “Calculation” and “Result Table”. All the required input data are summarized below:

- Travel Block weight (ton)
- Mud weight (S.G)
- Total Well Depth (m.)
- Casing shoe depth (m.)
- Friction factor case hole
- Friction factor open hole
- Rotary pipe Speed(rpm-rotation per minute)
- Axial Velocity(m/s)
- Weight on bit (ton)
- Torque on bit (ton)

Drill string Configurations:

- Length (m)
- Weight (ton)
- Tool joint OD (m)
- Pipe Density (S.G)

Well Section:

- Length (m)
- Inclination (degree)
- Azimuth (degree)

As it could be noticed from input data, base on the actual survey, inclination/azimuth versus measured depth a well must be separated into the sections. Software does not take into account any tortuosity and assumes that wellbore has a smooth profile, and curved section has equally distributed build-up/drop-off and turn rate. Due to such software limitation the actual wellbore has to be carefully divided into the section and any possible so called subsection in order to include a wall contact forces.

The simulator includes also the weight on bit (WOB) and torque on (TOB) values which is required to apply during the drilling operation. Torque and drag prediction during the drilling operation, i.e. with application of WOB and TOB, has not been included in the calculation.

During the surface torque calculation, it is required to use tool joint OD size.

Based on the industry experience regarding the friction factor behaviour which states that it is not always the same for slack off, pick and rotation operation, the simulator was made to be able to use various friction factors for the selected operation. Detailed instruction of how to use simulator with attached screen shot included in the Appendix B.

2.1 Limitation and future work regarding the simulator

During the manual calculation with the analytical model, inclination and azimuth of some depths such as switching from one pipe size to another and also from cased hole to open hole, are picked up from survey data. By this we are able somehow control wellbore irregularities. This approach increases an accuracy of the calculated results. However with 3D Model Software, the simulator finds the coordinate by the approximate calculation. This approach assumes smooth wellbore profile with constant build up and drop off rate and by this excludes tortuosity. Of course it has affect to the calculation results, but the difference based on the comparison is less than 5 tones.

In order to use the analytical model in its full power, it also requires an application of the complete solution. The software may preliminarily, investigate the effective tension in a drillstring along the entire wellbore and on the later stage based on the results determine required solution and equations. 3D Model on the current stage only uses the simple solution, which can introduce an error in the particular cases. Additionally, as it was mentioned, 3D Model requires that the wellbore has to be divided into the section by a user. As a future work, the simulator may be modified in a way that, it would be able to read survey data and determine exact inclination and azimuth values in any required measured depth. In this case, the simulator could also distinguish the well sections based on the imported surveys automatically, the same way as by Wellplan software.

3. Wellplan Software

Wellplan is widely used drilling engineering software for drilling, completion, and well service operations. Wellplan software can be used at the rig site and in the office to provide integration between engineering functions. The software is able to solve number of technical challenges such as extended-reach drilling, slim-hole drilling deepwater drilling, and environmentally sensitive drilling areas and etc.[7,21]The software is used during the design and operational phases for drilling and well completion.

Wellplan torque and drag model does not include wellbore cleaning aspects and assumes that all the cuttings are removed. The real picture of course is much more complicated. Depending on the hole section, drilling parameter, drilling fluid properties, penetrated formation and number of other factor the cutting removal behavior will be rather complex.[21]

3.1 Torque & Drag Module

The Torque & Drag module in Wellplan software 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, back reaming. Based on the simulation results, engineers are able to determine if the well can be drilled, or to evaluate what is occurring while drilling a well.

Torque Drag is based on Dawson's cable model, or so called "Soft String" model. This approach assumes zero bending stiffness in a pipe which treated as an extendible cable. Additionally, a “Stiff String” model is provided as an option. This model includes the increased side force from stiff tubular in curved hole, as well as the reduced side forces from pipe wall clearance. The stiff string model is not available for the Drag Chart[7]. Along with this, the effect of mud properties, wellbore deviation, tortuosity and other parameters can also be studied and applied by using Torque & Drag application.

Wellplan torque and drag calculations contains the following applications:

- Axial Force Calculations
- Drag Force
- Sheave Friction Correction
- Side Force for Soft String Model
- Torque
- Viscous Drag

Master thesis includes simulation results from Wellplan 5000.1 version. Along with this, there is simulation results received from service companies which was done in Wellplan 2003 version.

4. Test Well Application

The master thesis has objectives to investigate the reasons behind the discrepancy between the analytical model and Wellplan Software. Even though, the true model verification must be through comparison of it with actual measured data, based on the recommendation from model authors, there is a big interest to have a clear picture regarding the analytical model relationship with Wellplan Software. The mentioned software has a wide application in industry and received an approval from most the leading industry companies. In addition, the discrete model was also used for analysis in one of the test wells.

In order to fulfill current task, the master thesis uses number of synthetic wells. In a complex actual wellbore profile, it is rather challenging to evaluate and give an explanation of the discrepancy between Wellplan and the analytical model simulations results. And therefore the fiction wells have been chosen. By keeping the simple 2D wellbore profile by staged changing of the well trajectory parameters the five separate cases has been evaluated. Appendix C includes all the information relevant to these test wells.

As a primary objection it was decided to calculate drag forces. All the input data both in Wellplan and 3D model are identical. The friction factor applied in simulation is equal 0.24 both for open and case hole. All the BHA assembly, in Wellplan was united under one component drill collar to be exact within the 3D model. In the Wellplan the tortuosity model was not included. This option is used to roughen up a planned wellbore, to make it more realistic having undulation and irregularities. However in our current comparisons the main goal is to have smooth wellbore profile without tortuosity to comply with the analytical model assumption.

4.1 Test Well 1-Result and Discussion

The synthetic Test Well 1 has a simple well profile, with well section shown in Table 4. α 2, 1 and φ 2, 1denotes inclination and azimuth at the start and end of the well section. The sail angle has 50 degree of inclination and 3040 m section length. A curved section length is 410 meter. Travel block weight was chosen equal to 40 ton. Mud weight is 1.38 S.G. Total well depth is 4000 m M.D having casing shoe depth at 3150 m. M.D.

Table 4: Test well 1 well section survey

Well section	Length	Inclination		Azimuth	
		α_2	α_1	φ_2	φ_1
Straight Vertical	550	0	0	0	0
Build-up section	410	0	50	0	0
Inclined-Tangential	3040	50	50	0	0

The simplified drillstring configuration and all Wellplan reports are included in the Appendix C.

The analytical model application was done both with manual calculation and 3D Model simulator. The last gives a hook load weight versus the measured depth plot which gives us an opportunity to compare the curve profile with the simulation results from the Wellplan.

Table 5 gives numerical values for the hook load results simulated with the three mentioned methods. The discrepancy between the analytical model and the Wellplan for tripping out operation at total well depth is 0.77 ton, while this difference with the discrete model is 3.4 ton. The slack-off and rotating-off bottom value comparison give very similar results.

Table 5: Weight on Hook Load at Total depth-Test Well 1

Hook Load Values	Tripping in (ton)	Tripping out (ton)	Rotating off bottom(ton)
Analytical Model	100.63	161.11	125.92
Wellplan	100.54	160.34	125.61
Discrete Model	100.89	163.79	-

Table 6 presents the analytical model simulator results for each well section for three operations slack off, pick up and rotating off bottom.

Table 6: 3D Model the hook load simulation results

Depth(m)	Slack-off (ton)	Pick- up (ton)	Rotating of bottom (ton)
0	40.00	40.00	40.00
550	62.77	62.77	62.77
960	70.86	71.80	71.32
4000	100.63	161.11	125.92

Figure 7 shows comparison of the hook load weight versus measured depth.

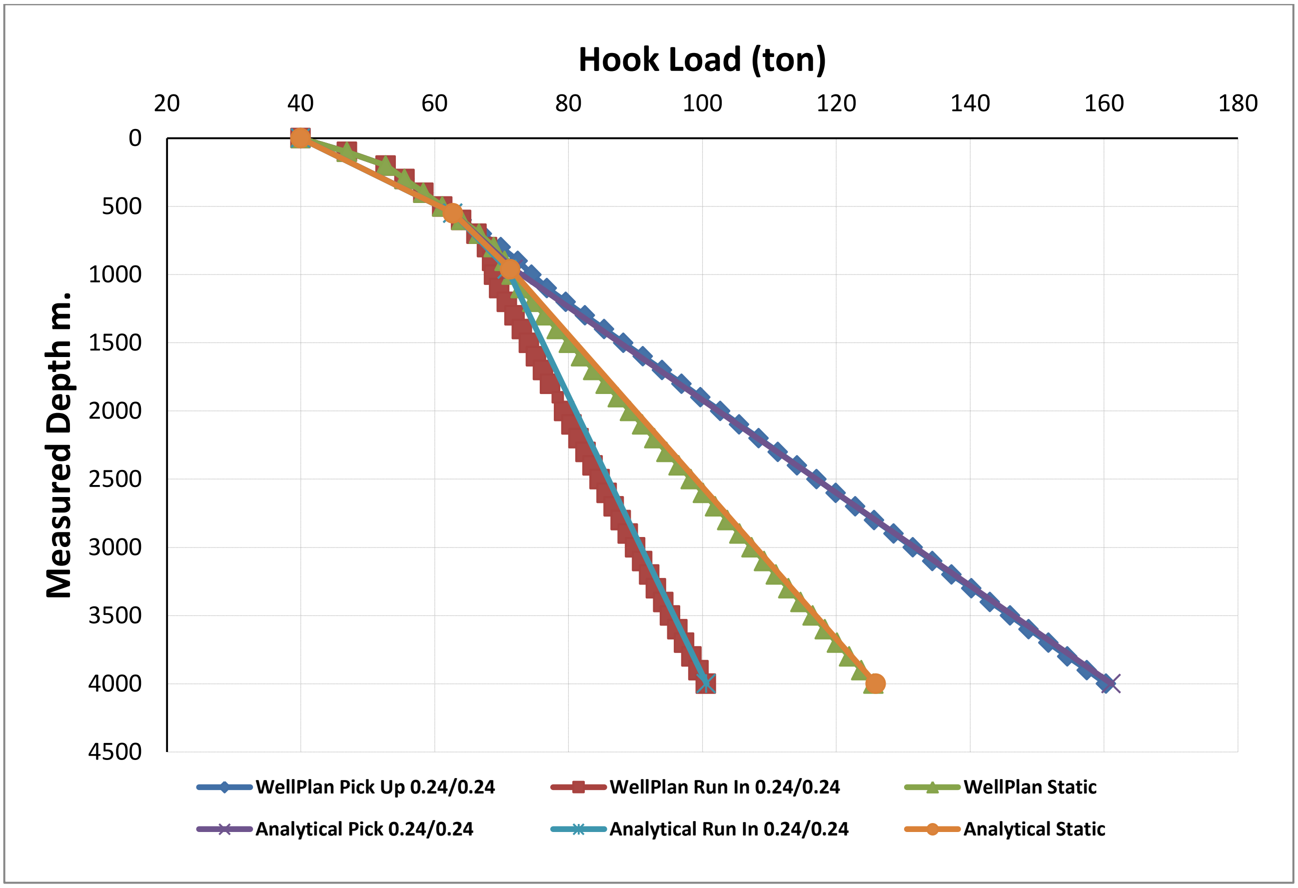

Figure 7: Comparison between hook load weight, the analytical model vs Wellplan simulation-Test Well 1

As it can be observed from the Figure 7, there are a good match between the analytical model and Wellplan. Curves profile for all three measurements; rotating off bottom, pick up and slack off overlap. Some portion of discrepancy between the model and Wellplan could be due to the mud rheology, which is not taken into account by neither analytical nor discrete model. For the Wellplan the mud rheology was chosen as a Bingham model.

It is interesting that the comparison between the discrete manual calculation and Wellplan simulation results shows discrepancy. During the pickup operation the difference is more than 3 ton, which for the simple wellbore profile could be considered as a big. The difference has increasing tendency with increasing of the number of segments in a curved section in the discrete model calculation. The discrete model has been calculated with separation of curved section into different number of segments. The results are the following; the pickup drag results have a slight increasing tendency with increasing the number of segments. Having a soft string assumption it could be concluded that by increased number of segments in a curved section, the hook load weight overestimation is also increases. However, it is not the same for slack off calculated values which was expected to decrease due to the soft string assumption. With increased number of segments it has slightly increasing tendency as well, Table 7.

Table 7: Discrete model calculation results

Number of segments in curved section	1	2	4	8	10	41
Length of the single segment (m)	410	205	102.5	51.25	41	10
Pick-up (ton)	160.81	162.52	163.23	163.55	163.61	163.79
Slack-off (ton)	98.90	100.20	100.63	100.79	100.82	100.89

From the difference between discrete model and Wellplan, may be concluded that that Wellplan does not use exactly the discrete model in its application as it was supposed earlier. The software must probably include other correlation factors to the simulation results based on the thorough theory and industry experience.

Figure 8 shows the effective tension distribution along the drillstring obtained from Wellplan software. The positive values indicate that the drillstring in tension while the negative shows the compression in the drillstring. This plot also indicates the tension limit for the drillstring element at the corresponding measured depth. The red line to the left is the buckling limit when there is no rotation, while the red lines to the right are the tension limit of the rig and drillstring when tripping out.[7, 23]The tension limit was chosen to be 90% of the yield strength limit of the string.

In the Test Well 1, during all the operations, stripping in/out and rotating off bottom operations the drillstring is in tension having the maximum value on the surface and approaching to zero at the bottom of the well.

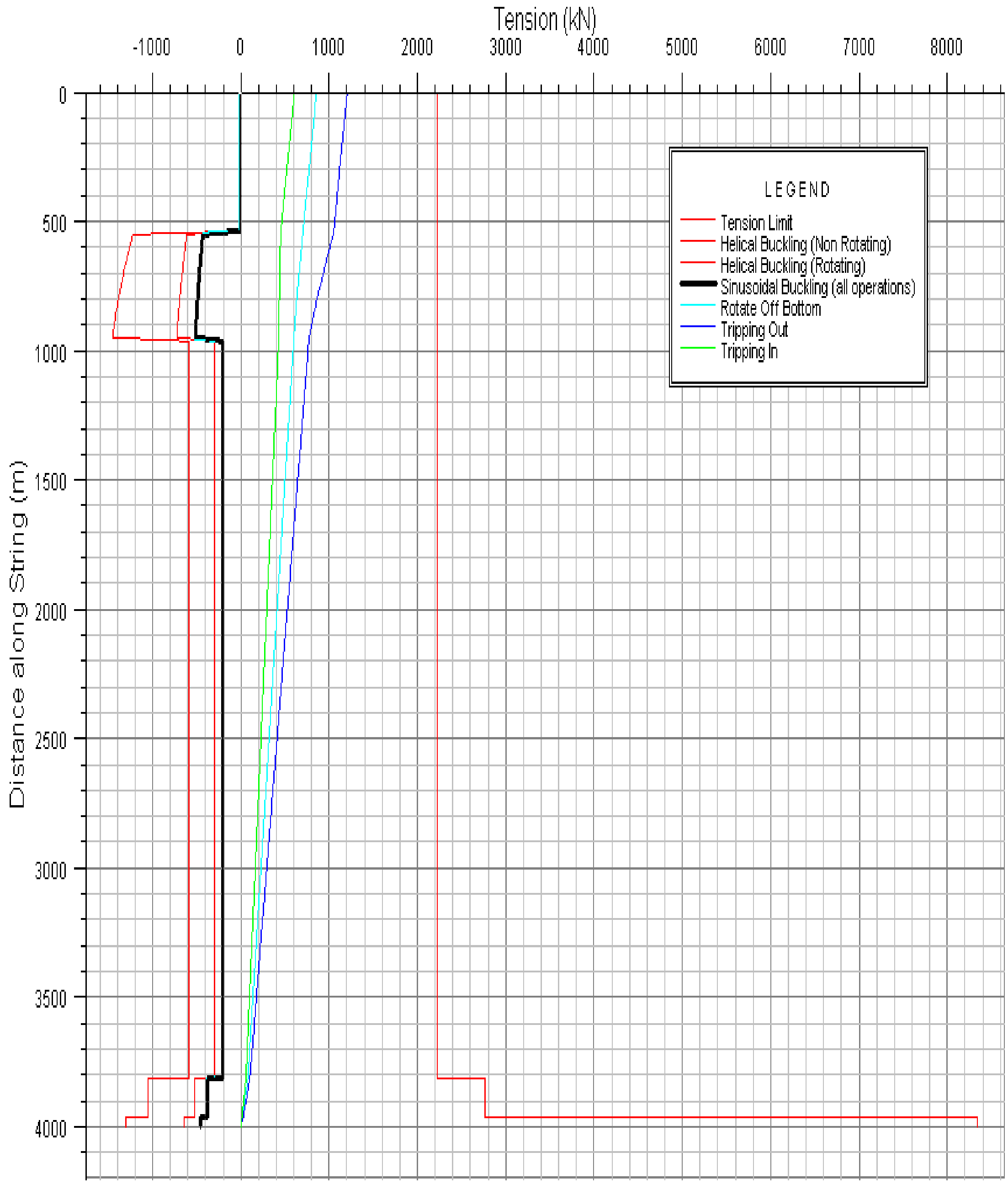

Figure 8: Effective Tension Test Well 1

4.2 Test Well 2-Result and Discussion

Test well 2 was changed by increasing a curved section length till 700 meters. The length of the vertical and sail sections are the same as in a previous test. Table 8 shows the weight on hook load at total well depth simulated with the 3D model and Wellplan software. The results again are similar having the discrepancy less than 1 ton.

Table 8: Weight on Hook Load at Total depth-Test Well 2

Hook Load Values	Tripping in (ton)	Tripping out (ton)	Rotating of bottom (ton)
Analytical Model	107.86	168.34	133.15
Wellplan	107.76	167.37	132.82

Figure 9 and 10 shows hook load and torque off bottom values verses measured depth respectively.

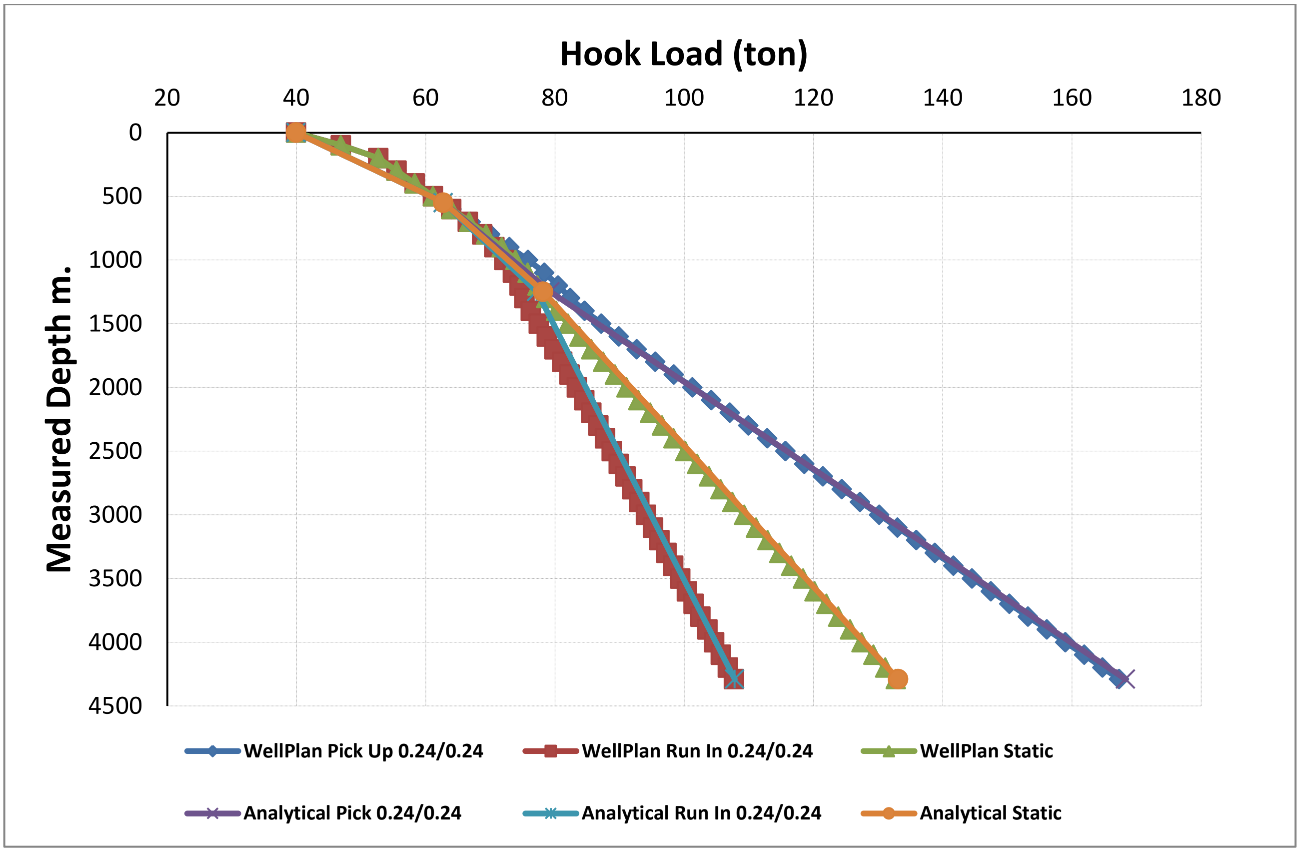

Figure 9: Comparison between hook load weight, the analytical model vs Wellplan simulation-Test Well 2

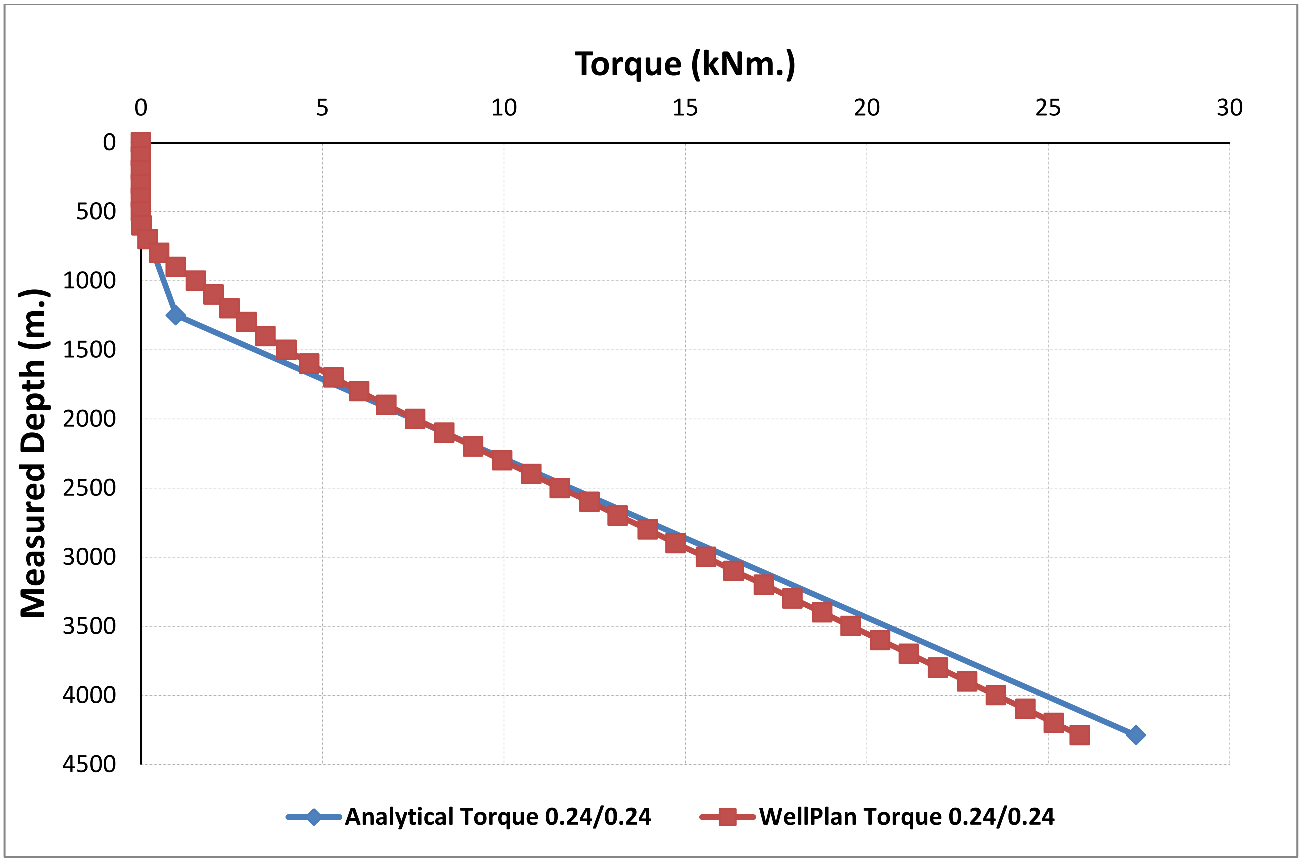

Figure 10: Comparison between torque-off bottom, the analytical model vs Wellplan simulation-Test 2

From Figure 10, the difference between torque-off bottom values is 1.5kN.m. The analytical model curve profile has a sharp intersection between calculated points comparing with smooth Wellplan curve profile. Such curve behavior is may be explained by the fact that the analytical model comparing with Wellplan includes "Capstan effect".[11,20] Additionally, one of the features of the analytical model is the fact that during the torque calculation it uses tool joint radius, while software use pipe radius or an average values of pipe and tool joint sizes[7]. This may be the reason of the discrepancy.

The effective tension plot, Figure 11, shows that the entire drillstring is in tension during all the operations.

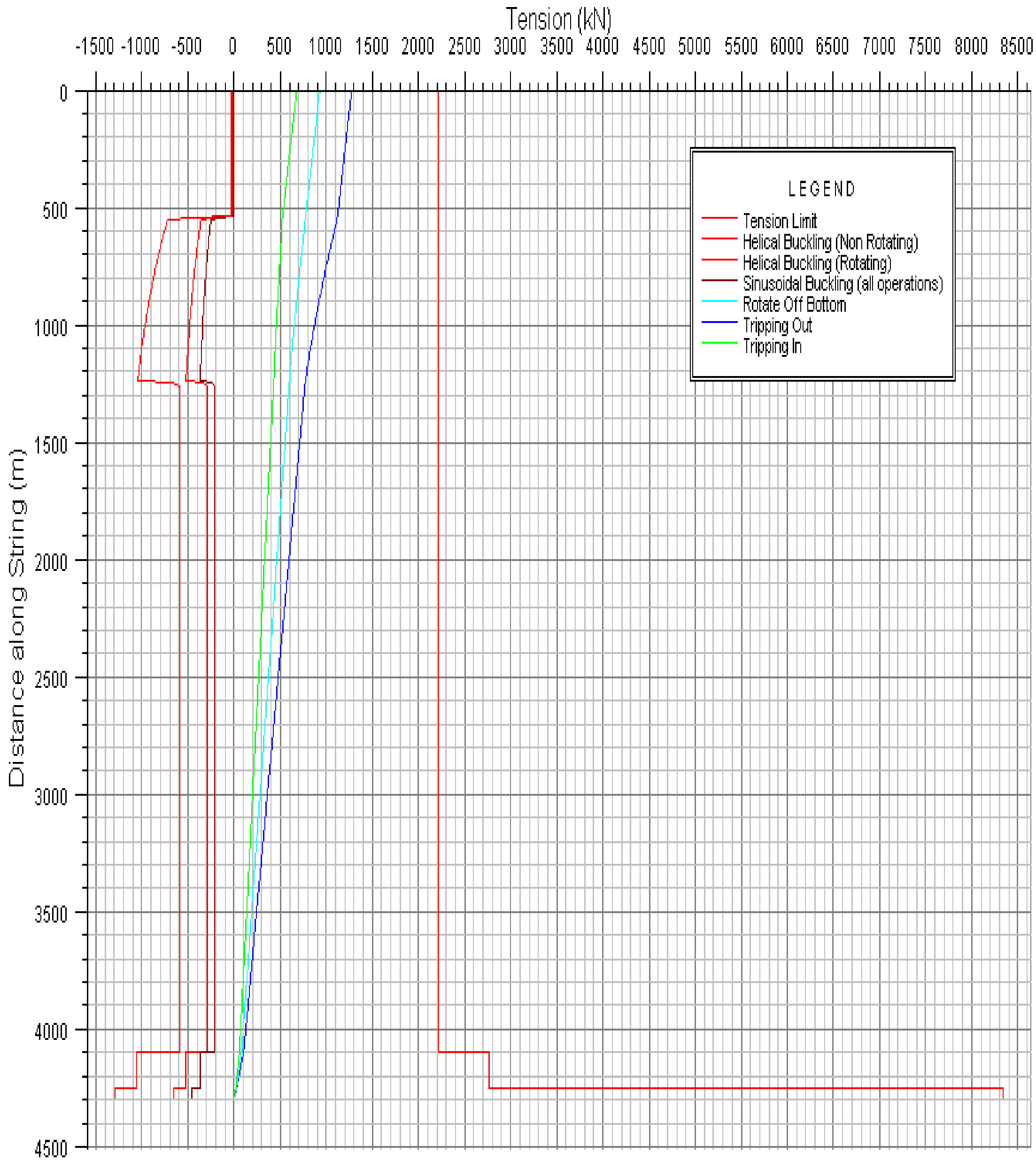

Figure 11: Effective Tension Test Well 2

As a brief conclusion for the first two test wells, may be that the prediction results overlaps quite good for slack off and rotating off bottom operations. There is some discrepancy about 1 ton in pick up results. The entire drillstring is in tension during all three operations, which satisfies the main requirement of the analytical model. This means that, current small difference between pick up predictions may increase in the complex actual wells. This discrepancy is not caused by the drillstring tension, which is high for both first two test wells. The torque off bottom comparison also gives some difference, which may be due to the Wellplan "Contact force normalization length" application. The "Capstan effect" which is taken into account by the analytical model explains the curve profile.

4.3 Test Well 3/4-Result and Discussion

Test wells 3 and 4 have the 80 degree sail angle over the 3040 measured well section interval. The curved section length is 410 and 700 meters respectively. The difference obtained between the Wellplan and the analytical model predictions for both wells are quite similar, Table 9&10. Tables give the hook load weight at total well depth and corresponding differences.

Table 9: Difference in Hook load weight simulated in Wellplan and 3D model-Test Well 3

Hook Load Values	Tripping in (ton)	Tripping out (ton)	Rotating off bottom (ton)
Analytical Model	59.64	117.41	80.06
Wellplan	54.75	116.17	79.93
Difference in Results	**4.89**	**1.24**	**0.13**

Table 10: Difference in hook load weight simulated in Wellplan and 3D Model –Test Well 4

Hook Load Values	Tripping in (ton)	Tripping out (ton)	Rotating of bottom (ton)
Analytical Model	65.45	123.22	85.87
Wellplan	59.79	121.42	85.72
Difference in Results	**5.66**	**1.80**	**0.15**

The main discrepancy occurs during the slack off operation. The difference is around 5 tons. Tripping out drag values show the difference around 1.24 ton. The rotating off bottom- static value has the same constant variance as in the previous tests. The slightly higher difference gives Test Well4, 5.7 tons for slack off and 1.8 ton for pick up operation. The longer the curved section bigger the discrepancy.

Figure 12, the curve trends for slack off and pick up operations in both Wellplan and the analytical model prediction are the same throughout1250 and 4290 measured interval. The shift between curves, which finally causes to discrepancy, happens in the buildup section, point A on figure.

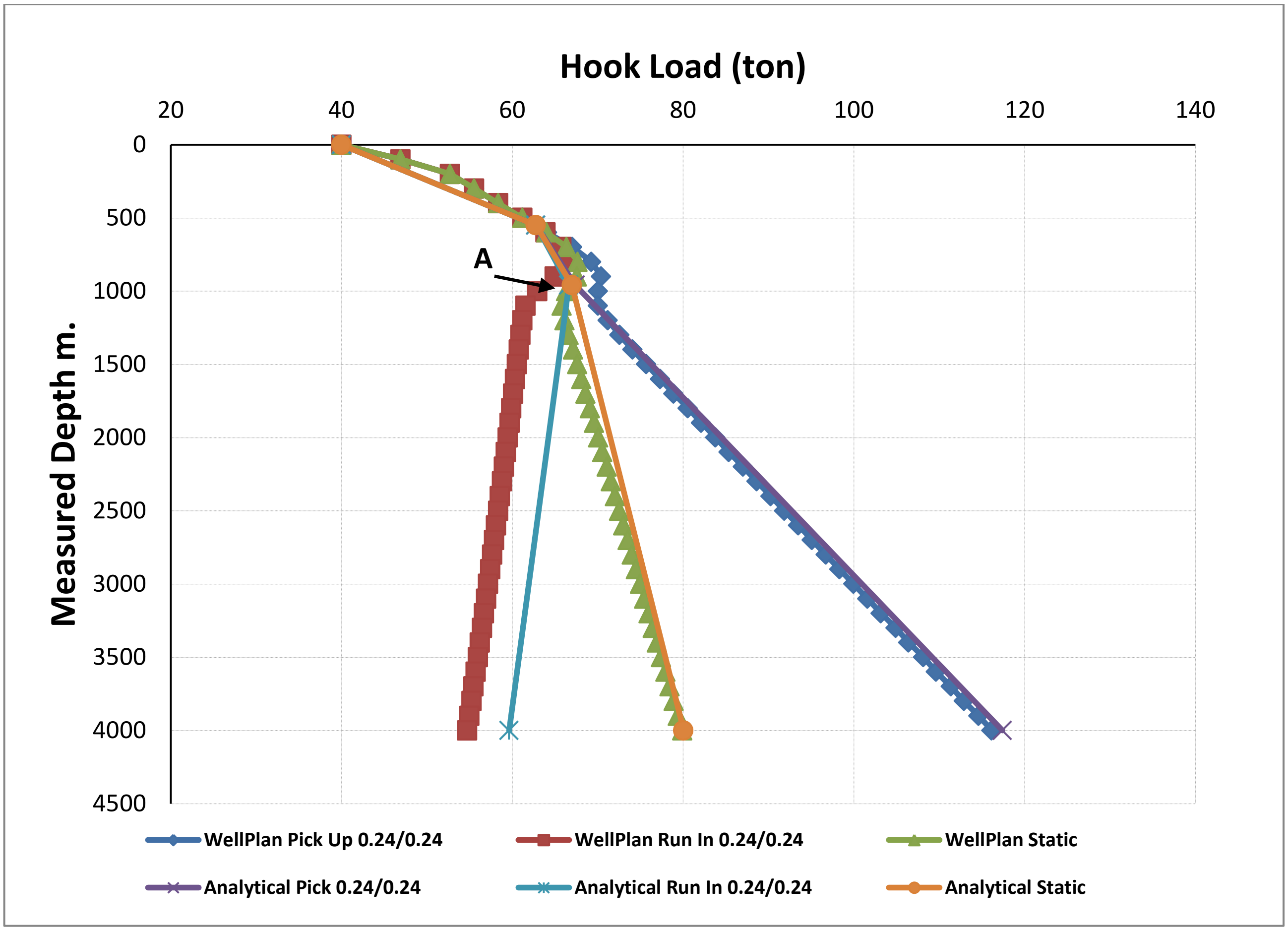

Figure 12: Comparison between hook load weight, the analytical model vs Wellplan simulation-Test Well3

The effective tension plot, Figure 13, 55 (Appendix C), observation gives a clue to explain the difference obtained in the slack off operations. The drillstring during the tripping in operation is switching from tension to compression having a neutral point at 540 m MD. Below this depth the drillstring is in compressed condition. Along with this, during the pickup operation the drillstring tension values along the entire measured depth is low compared with two previous test wells.

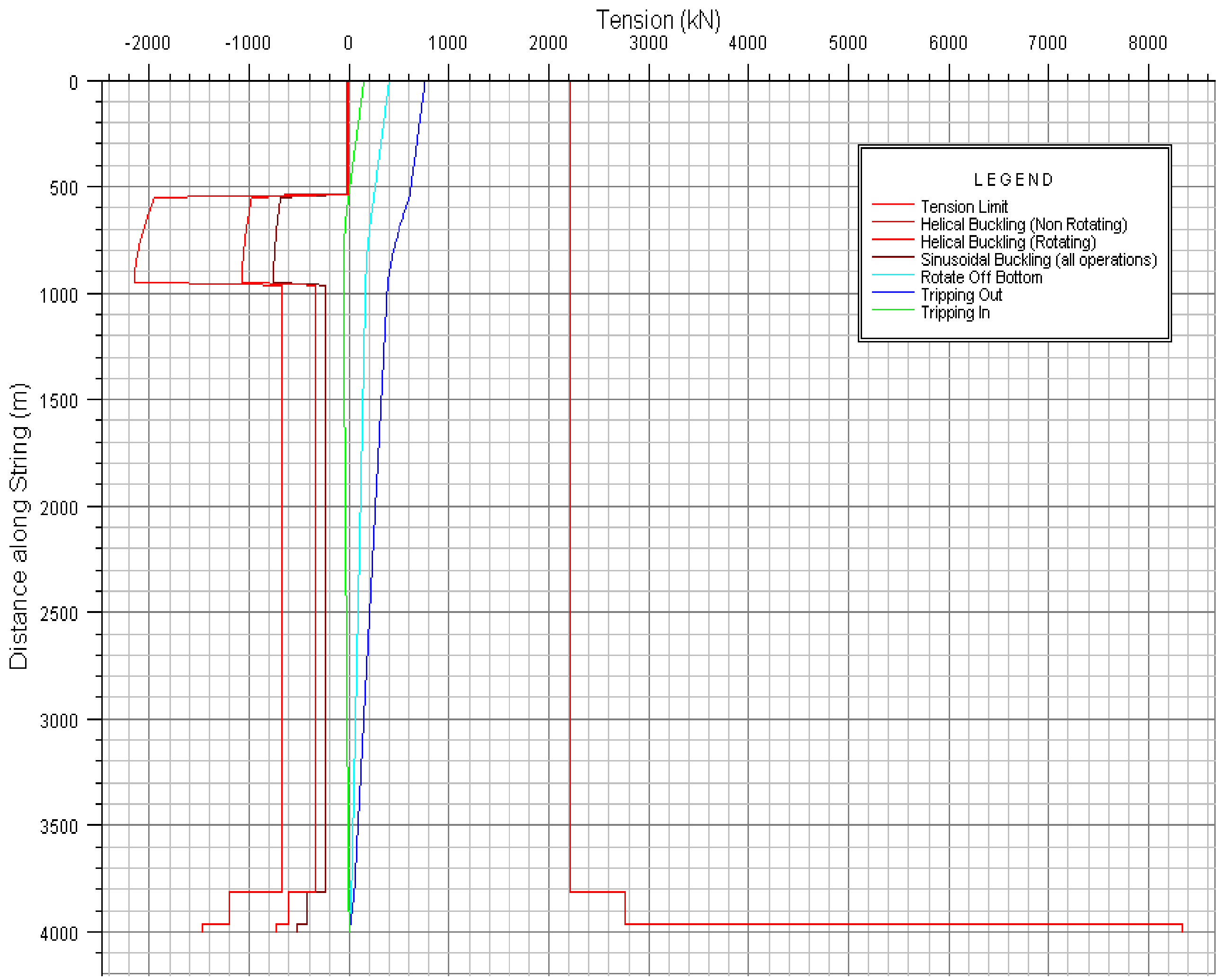

Figure 13: Effective Tension Test Well 3

Test Well 5 introduces 3d-dimentional trajectory by including wellbore azimuth changes as well. The torque and drag comparison between the analytical and Wellplan gave the similar discrepancies as in the previous test wells. Appendix C includes Test Well 5 simulation results.

4.4 The Complete Solution for Curved Section in Test Well 3&4

As it was stated early in the thesis, the analytical model introduces the complete solution for the curved section whenever the tension/compression is low to contribute for the wellbore friction. The 3D simulator was created based on the simple solution assumption and thus all the previous test well calculation were based on this approach. To further investigate the reason of discrepancies in the predicted hook load weight, the complete solution for wellbore curved section was applied. Hand calculation gives results only for the hook load weight when the drillstring is at total depth. The complete solution was applied for the Test Well 3 and 4.

Table 11 and 12 shows that the analytical model complete solution gave quite close results with Wellplan simulation. The difference in slack off values diminishes from 5 ton till 0.21 ton. The discrepancy reduces during pick up operation as well, from 1.24 ton till 0.40 ton. However there is still some variance between the predictions. This discrepancy may increase with application of more complex actual wellbore profile.

Table 11: Difference in Hook Load weight simulated in Wellplan and 3D Model-Test Well 3-The Complete Solution

Hook Load Values	Tripping in (ton)	Tripping out (ton)	Rotating of bottom (ton)
Analytical Model	54.79	116.57	80.06
Wellplan	54.75	116.17	79.93
Difference in Results	**0.04**	**0.40**	**0.13**

Table 12: Difference in Hook Load weight simulated in Wellplan and 3D Model-Test Well 4-The Complete Solution

Hook Load Values	Tripping in (ton)	Tripping out (ton)	Rotating of bottom (ton)
Analytical Model	60.00	121.77	85.87
Wellplan	59.79	121.42	85.72
Difference in Results	**0.21**	**0.35**	**0.15**

4.5 Conclusion to Test Wells

There is a good match between Wellplan and the analytical model during pick up, slack off and rotating off bottom operations when the drillstring is in tension. The discrepancies occur when the drillstring is partially in tension and partially in compression having a neutral i.e. switching point in some depth. The discrepancy also increases when the tension values due to the wellbore complexity starts to decrease.

The analytical model is strong function of effective tension in a drillstring. An application of simple solution gives a big difference in hook load weight predictions. While the complete solution applied for the curved wellbore sections decrease this discrepancy. Therefore it is important to evaluate effective tension and a neutral point along the drillstring to distinguish the suggested solutions.

Based on the Test 3, 4, 5 results it may be concluded that with application of the analytical model simple solution higher friction factor may be applied during slack off operation to get good match with Wellplan simulation. This suggestion comes from the analytical model assumption which assumes that drillstring is either in tension or compression, and their values are significant to contribute to friction factor along wellbore. Having a neutral point an error may occur.

It is worth to mention that most of the simulators, including widely used in oil industry Wellplan includes a number of correcting factors.[11]This makes quite challenging to compare the predictions. Therefore an optimal way for the analytical model evaluation is its application and testing in actual well with measured data.

5. Real Well Applications

5.1Calculation and Simulation Concern

The primary objective of the master thesis is to evaluate a potential and limitation of the analytical model by application it in the actual well for torque and drag simulation. The aim is the get the reasonable torque and drag predicted results compared with the field measurements.

To be able to apply the analytical model to the real well it is required to simplify wellbore into the section. The simplification assumes that wellbore has constant build up/drop off rates for the curved sections. All the wellpath have been divided based on the actual survey data, inclination and azimuth changes versus measured depth. The wellpath separation is quite challenging because actual wellbore survey usually are vague which makes it difficult to exactly distinguish well sections. So in general we get smooth wellpath, while the real wells contain severe doglegs and other irregularities. This assumption will be carefully noted during the comparison as it may be the reason behind of some discrepancies.

The quality check and comparison of the torque and drag simulation results was accomplished with Wellplan software. All the wells have been simulated by Wellplan 5000.1 version and some Wellplan 2003 version results are presented by service companies as well.

Many experience show that friction factor is calibrated depending on a model which is applied to torque and drag simulations, in order to be able to better fit actual field measurements. Current master thesis has a strict strategy to apply the same friction factor for both Wellplan and the analytical model:

- 0.18- for a cased hole
- 0.24-for an open hole

The torque and drag values was simulated and investigated during the tripping in/out, rotating off bottom operations. Based on the field experience and statistics the most stuck pipe failures happen mainly during these operations, about 40%[10]. Therefore it is very important that torque and drag models give clear prediction during running in and out motions. Along with this, each well section has different challenges and various chances to get stuck. The most sensitive to the drillstring stuck is 8 ½” hole section, more than 60%[10].All the actual wells included into the master thesis introduces the measurements in this particular hole section. Torque and drag analysis during the combined motion is also included in the calculations.

Based on the test well analysis, it was concluded that drillstring tension/compression condition must also be considered during the analytical model simple solution application. Therefore effective tension plot, from Wellplan, will be included in order to better notice entire picture.

The master thesis tries to give full discussion and interpretation of acquired results. The well and drillstring details are included in appendixes. The purpose of showing the simulation is that the readers can go through the details and have a clear picture regarding the model behavior in the wells with different wellbores trajectories and total depth.

Due to the strict company rules regarding the well data distribution and sharing some of well name and data will be neutralized. The Gulltop and Oseberg field wells have received an approval for an open edition.

5.2 Uncertainties, Field Data Quality and Assumptions

This sub-chapter includes a list of all the uncertainties and assumption made during the torque and drag simulation both in 3D model simulator and Wellplan software. The following chapters discuss the possible errors caused by them.

The quality of the actual field data is crucial in order to eliminate misleading during the comparisons. It is important to have accurate and reliable field data for precise verification of the model. In general, it is worth to mention that the actual field data quality, used in the master thesis, is quite poor. Some of the data has been received as mud logs where all the measurements have a high fluctuation and uncertainties. Along with this, in some cases, there was a vagueness regarding the exact drillstring/BHA configurations used in particular operation. The data was filtered according to the depth to acquire the required measurements. In addition, there was an actual data obtained in a PDF format. In order to be able to compare the results with simulated one, the actual data was digitalized into the numeral with application of Dagra software. The mentioned operations do not exclude chances to make error.

Actual data supposed to include so called “the sheave effect” and it is assumed that actual surface hook load is measured based on draw works dead line tension measurements and surface torque based on top drive electrical current measurements[6].In general, it is a good practice to compare field data with static weight data to make sure the quality of measured data is acceptable.

There are uncertainties regarding the exact BHA and drillstring configurations when the available actual data has been measured. It is rather important because hook load weight and surface torque measurements are very sensitive to the drillstring and BHA component description. BHA input in the analytical model calculation (3D Model simulator) is rather approximated because it unions different components by averaging them. While the true BHA will consist of different parts shapes, weights, and sizes. Wellplan software gives an opportunity to specify every single component in the drillstring. But sometime, due to the limited Wellplan 5000.1 catalogues, there was a problem with defining the specific component of the drillstring or/and BHA. The component was replaced by maximum identical one available from the list of catalogues.

Due to the complex wellbore profiles there are strict requirement to the drillstring configuration. It is important that planner engineer tried to eliminate acceptance of sinusoidal and especially helical buckling. In the current thesis, it is assumed no bucking occurs with the used drillstring assemblies. The results have been confirmed in Wellplan 5000.1 “Load Summary analysis” as well. However in the real cases it is possible to experience unexpected sinusoidal or even helical buckling which can be the reason of unexpected high friction forces. This may be caused by poor hole cleaning issues, wellbore instability and etc. Actual measurements, of course will be affected if this happens, as the side forces which appear as the results of mentioned situations have a tremendous effect on friction factor.[14]Without having detailed operational report from interested us operation, this will be uncertain.

The wellbore diameter is assumed to be constant. But actually due to the wellbore instability or cutting bed accumulation wellbore diameter may change. This causes additional surface contact and friction. The side force values will be affected and as the results the measured surface data will be shifted correspondingly. Asperity between the drillstring and wellbore is also neglected.

As it was mentioned early, the wellbore has to be simplified in order to be able to apply the analytical model. In this case the model does not take into account actual wellbore tortuosity and assumes that wellbore is smooth. Therefore to increase the model accuracy it is important that actual wellbore is carefully divided into the section and subsection. By this the model would be more sensitive to the dogleg and wellbore irregularities. Additionally, it is important to mention that even a small inclination changes ($0° < \text{inclination} < 2°$), in a vertical sections could has a big effect on the torque results[24]. Most of the included real wells have such slight inclination deflection on the surveys. The model assumes ideal vertical section with zero inclination from the surface to the kick-off point.

In all calculations it is assumed that mud density is constant during the entire operations. In reality, the buoyancy, which has an influence to the simulation results, is the function of mud density. And mud density can be changed by increasing or decreasing cutting concentration along the wellbore sections. The analytical model cannot take into account fluctuation in a cutting concentration. Along with this, the buoyancy equation during the calculations assumes that there is constant mud with same mud density in and out of drillstring (eq.3).The effect of hydrodynamic viscous forces; mud type's features are also neglected.

All the above mentioned assumptions were made to be as reasonable as possible to minimize their effect on the final values. All the possible discrepancies between obtained results will be discussed and tried to find the relevance of them with the made assumptions.

5.3 Real Well 1 Information

Real Well 1 is an oil producer drilled from semisubmersible platform with total measured depth equal to 6347 m. and TVD2814 m. TVD.9 5/8" casing liner shoe is set at 5999 m MD. 8 ½" x 10 ¼" open hole well section is approximately 348 meters. Water depth is 176 m and RKB – MSL distance is 43 meter. Mud weight is 1.38 S.G. Figure 14 and 15 shows vertical and planned views respectively from Wellplan 5000.1.

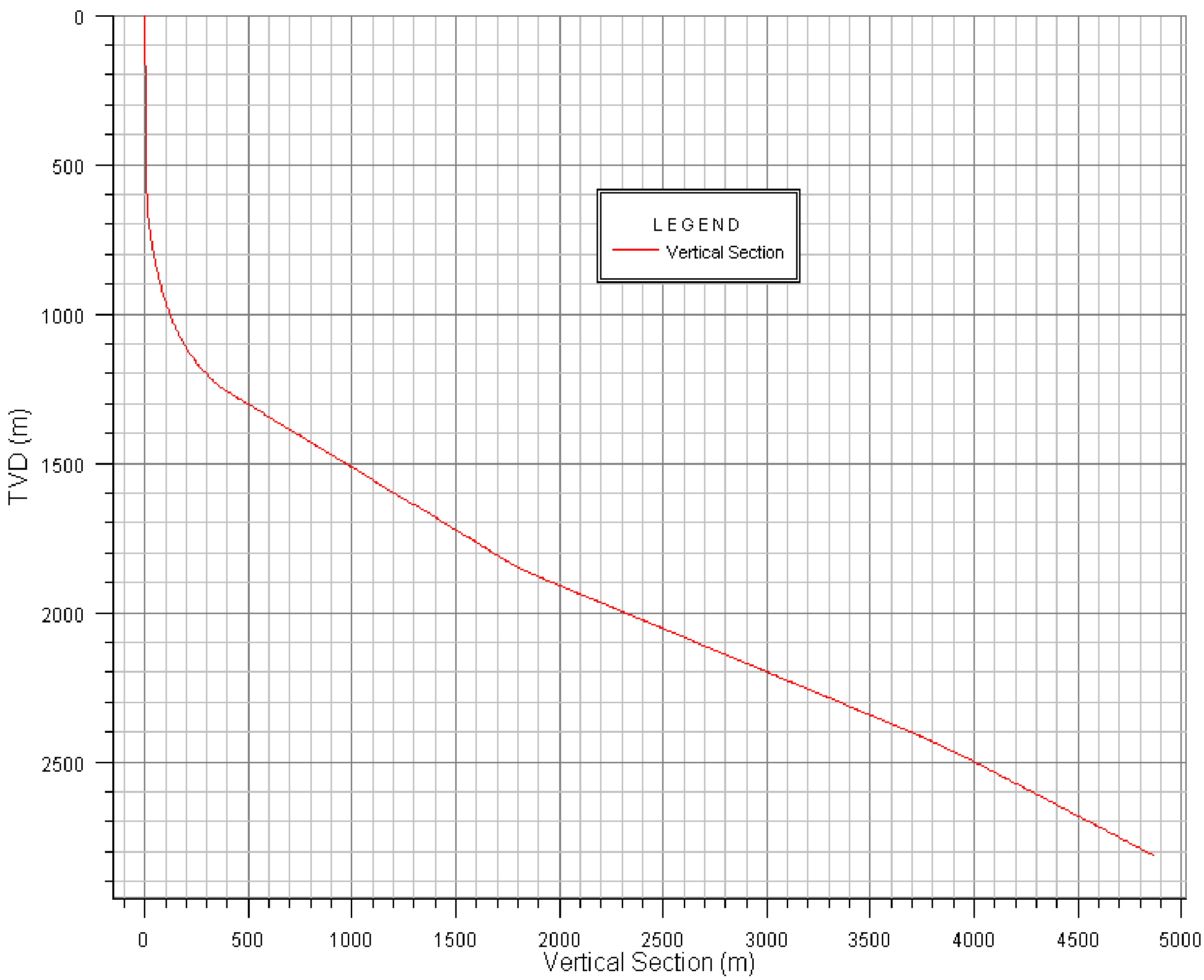

Figure 14: Vertical view -Real Well 1

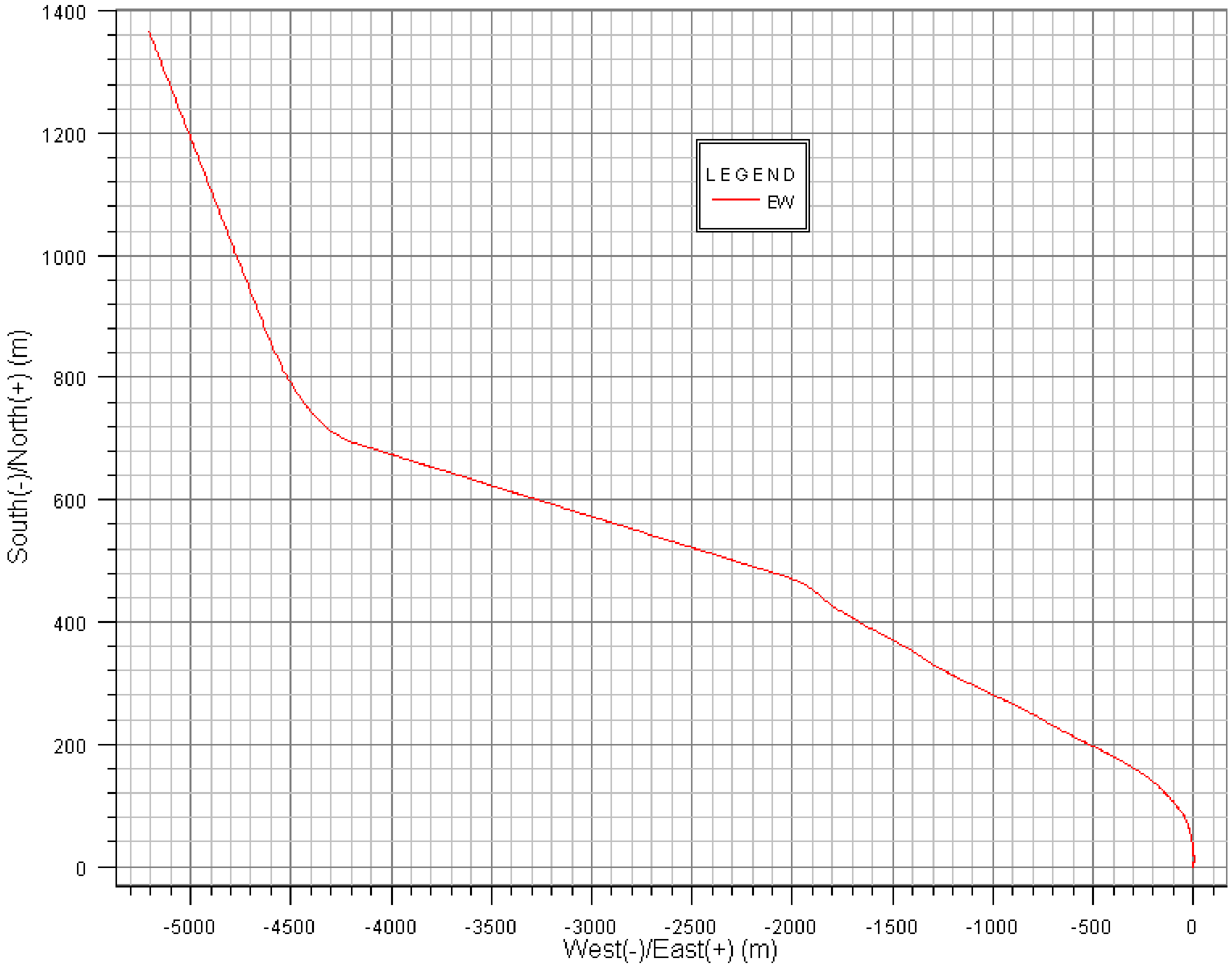

Figure 15: Planned View -Real Well 1

Table 13 shows the well sections which are included into the current well.

Table 13: Real Well 1 well section

Section Type	Measured Depth	Length	Inc	Az.
	MD	m.	α(°)	φ(°)
Vertical	0	457.2	0	345
Build up with left hand side	457.2	1036.32	0	345
Tangential	1493.52	1524	70	280
Build up with left hand side	3017.52	213.36	70	280
Tangential	3230.88	2225.04	76	276
Drop off with right hand side	5455.92	457.2	76	276
Tangential	5913.12	433.88	70	310
Total Depth	6347		70	310

All the detailed information relevant to the Real Well 1 is included in Appendix D.

5.3.1 Results and Discussion - Real Well 1

Figure 16 shows the comparison of Wellplan 5000.1 and Wellplan 2003 version received by Service Company. This was done in order to check the quality of applied data. Also this comparison helps us to determine any possible modification in the software version 2003 and 5000.1. With application of the same friction factors, 0.25 and 0.3 for case and open hole respectively, the slack off hook load values have a good match. The pickup values have a slight discrepancy coming close to the total depth. The discrepancy may be due to the sheave friction correlation in the "Torque Drag Setup Data".

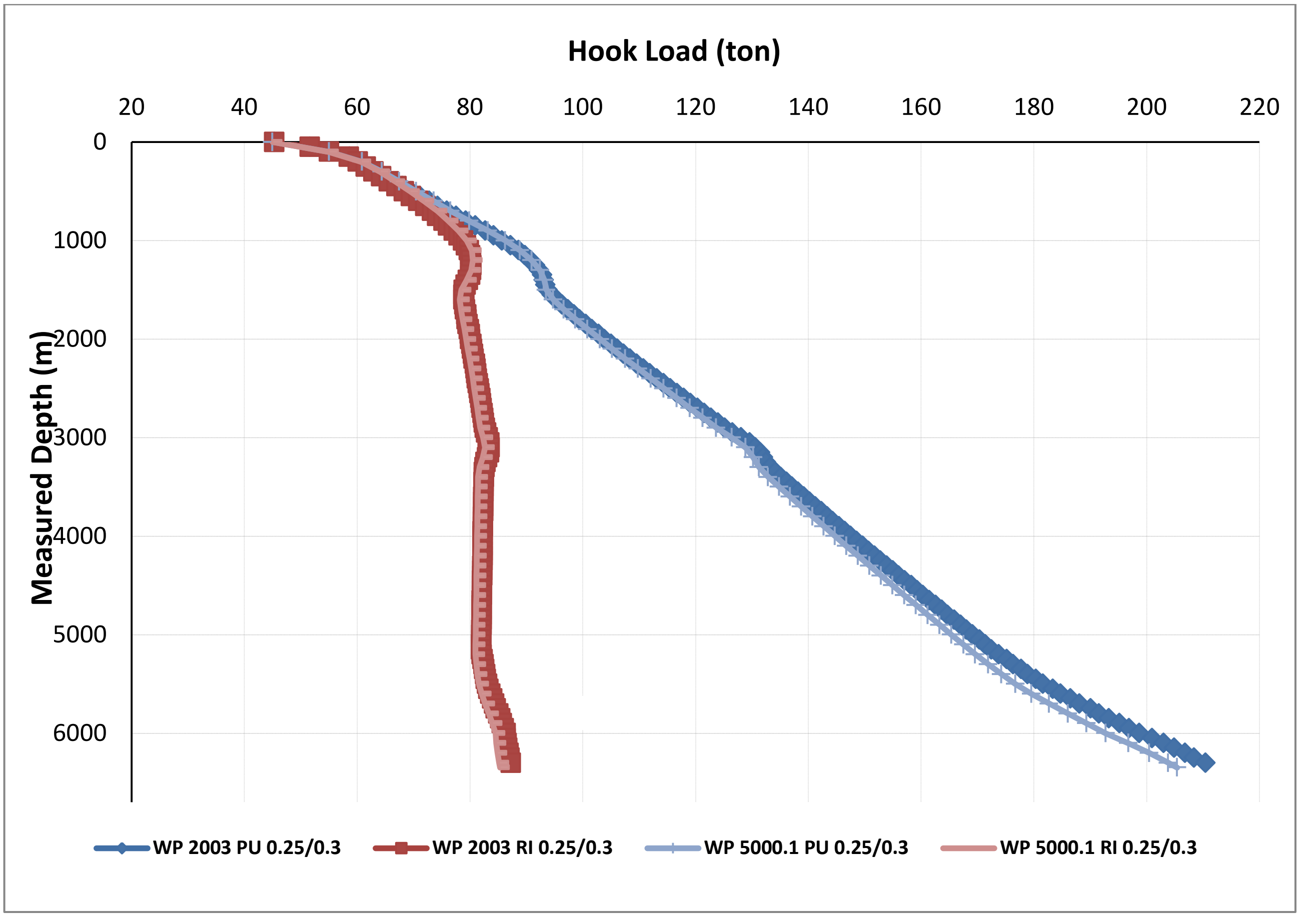

Figure 16: Comparison of Wellplan 5000.1 and Wellplan 2003 version

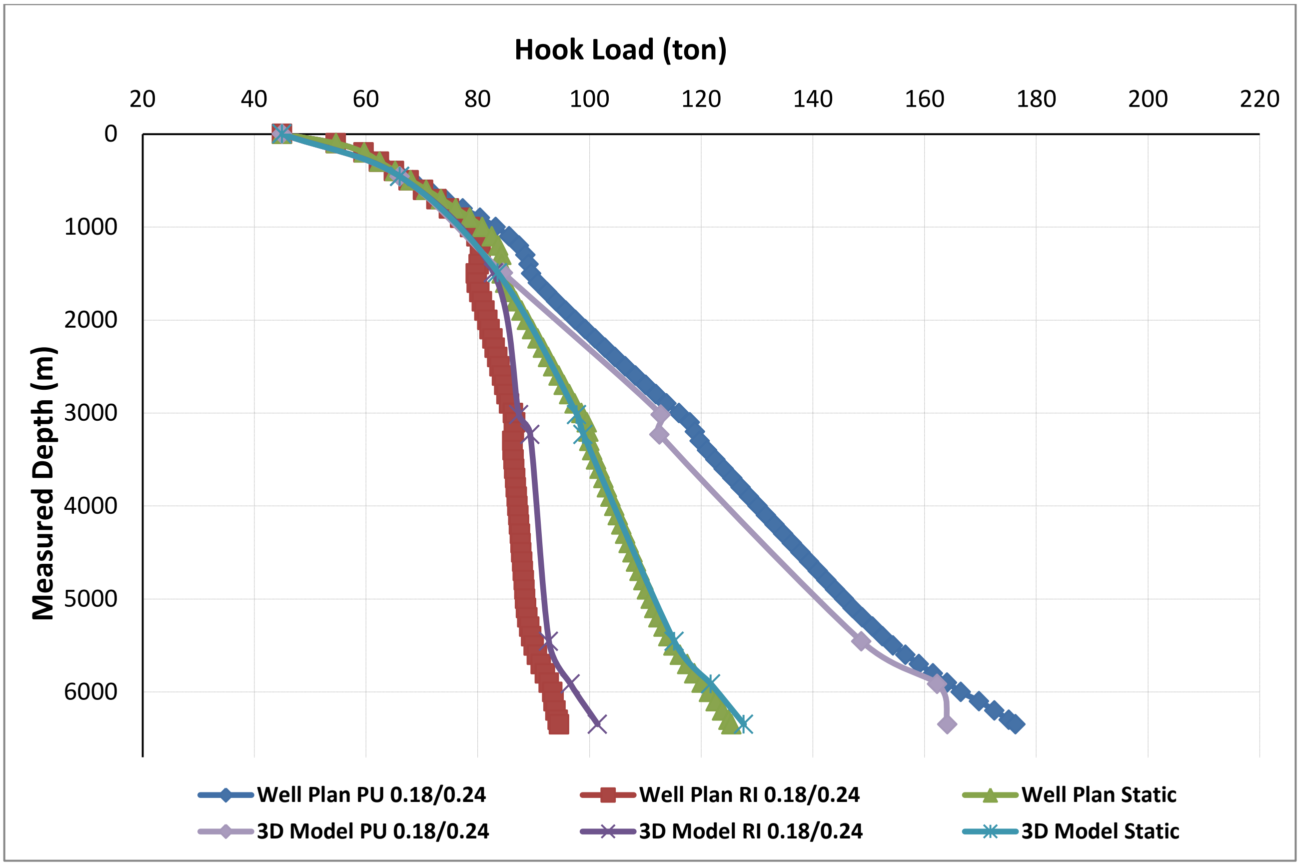

Figure 17: Comparison between 3D analytical model and Wellplan 5000.1 version –Hook Load Weight versus Measured Depth-Real Well1

Current Figure 17 compares the analytical model hook load values with Wellplan 5000.1 simulation results for tripping in/out and rotating off bottom operation. Friction factors applied in both calculations are equal to 0.18 for case hole and 0.24 for open hole. The rotating off bottom curve has a good match. The slack off and the pick up prediction of the analytical model have relatively constant right and left site shifts respectively comparing to Wellplan with the approximate difference equal to 5 tones. At the well bottom the difference increase till 10 ton for the tripping out operation. As the possible reasons of the discrepancy, could be the less tension value along the drillstring, Figure 60 Appendix D. The entire drillstring is in tension during all operations, however the tension values in tripping in is low and approach to zero starting from 3000 m MD.

Along with this, wellbore section in the current well has been simplified in order to be able to apply analytical model. Wellplan software has its own approach regarding the wellbore section separation. Taking into account analytical model this simplification, it might be acceptable to apply slightly high friction factor to take into account wellbore tortuosity and doglegs. With application of 0.2/0.25 friction factor, Figure 18, the difference is decreasing. Further in the thesis, we will not calibrate friction factor in the analytical model calculation in order to better fit with Wellplan. It was done in order to better understand the possible errors which could the reason of above mentioned analytical model simplification. And in general the master thesis does not have a goal to evaluate the analytical model by comparing it with Wellplan. The actual measurements must be used in order to check the model potential and limitations[11].

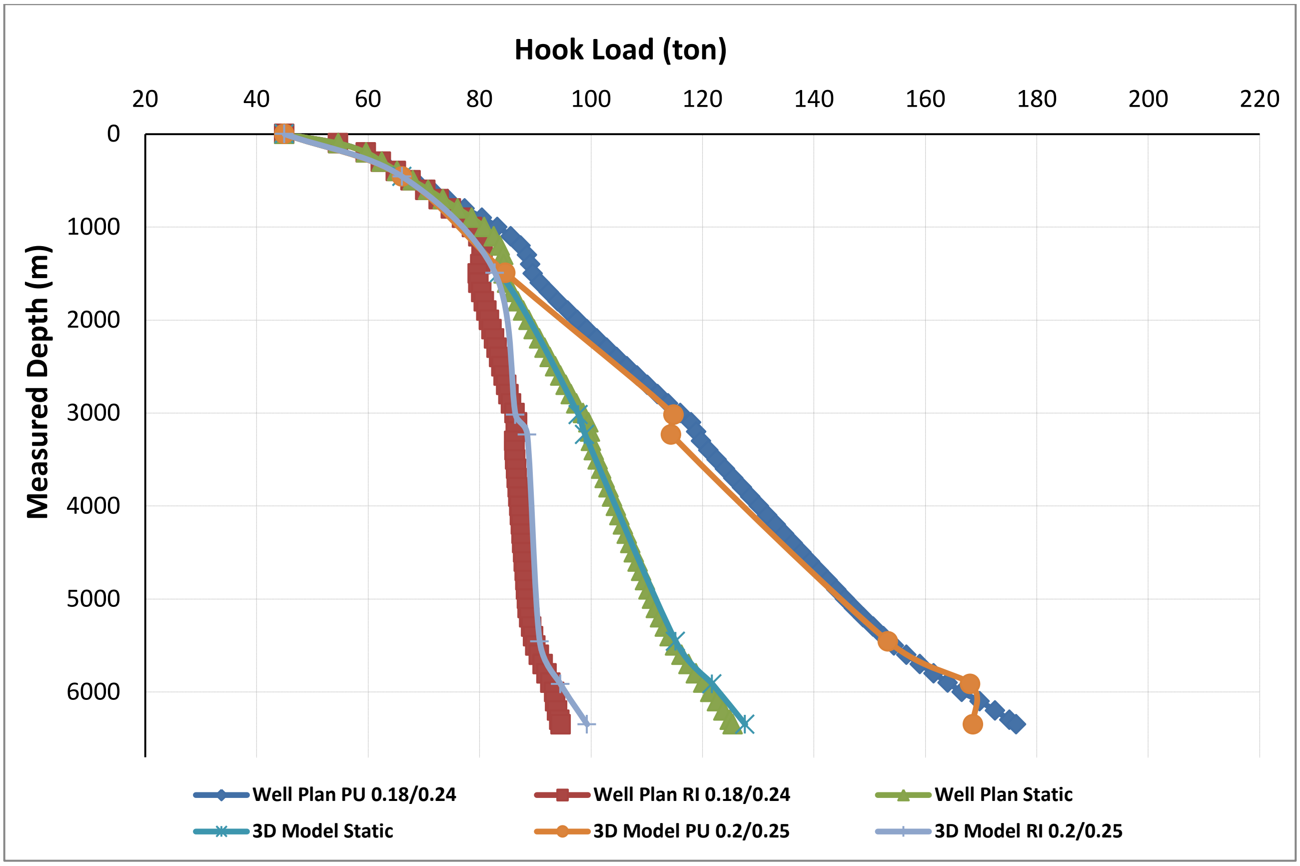

Figure 18: Comparison between 3D analytical model (0.2/0.25) and Wellplan 5000.1 (0.18/0.24) version – Surface Hook Load Weight versus Measured Depth-Real Well 1

The analytical model allows us to simulated, combined up and down operations. Figure 19 shows the comparison of purely tripping in/out operation with combined up/down motion. The drillstring is rotating with 60 rpm and applied axial velocity is 0.3 m/s. The purpose of such comparison is evaluation of the model behavior and validity in the combined operations. Based on theory the wellbore friction is split into rotation and axial friction.[1,2] By increasing one of them the other will decrease. During the both reaming and back reaming operations as the result of drill string rotation axial friction decrease and hook load indicates high and low values respectively. In Figure 19, the hook load weight of the drillstring at total depth during combined up motion decreased from 164 ton till 147 ton, while during the combined down this vales increase from 101 ton till 111 ton. It may be concluded that the analytical model behaves adequately according to the applied operation.

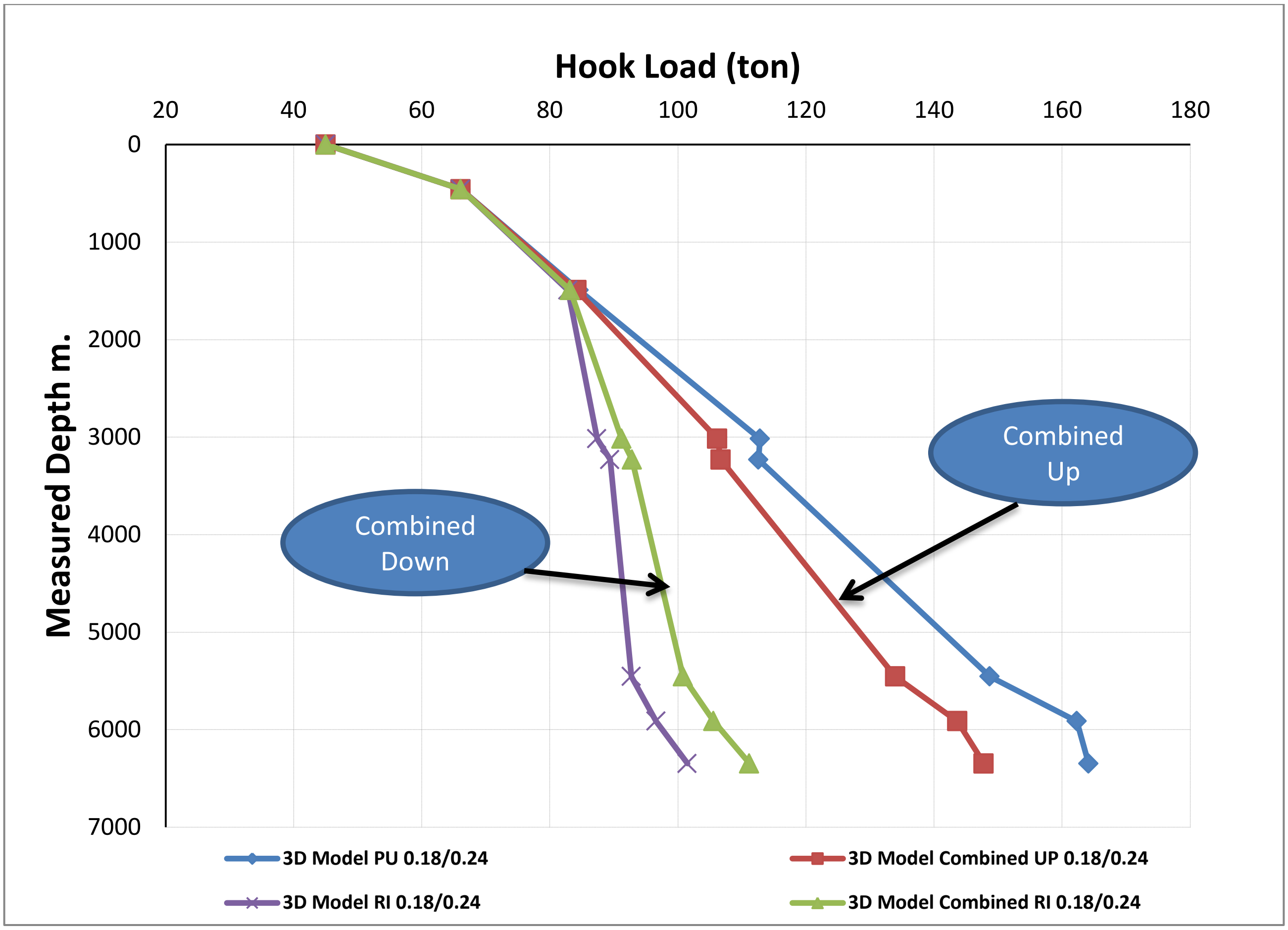

Figure 19: Effect of pipe rotation on the hook load weight while the tripping in and out operation

Combined up/down operations with the same input parameters have been simulated in the Wellplan 5000.1 as well. Figure 20 shows the comparison of Wellplan and 3D Model simulator results. Both curves have a good match. Once the axial drag in the string is decreased due to the applied rotation the discrepancy between the Wellplan and the analytical model is diminished.

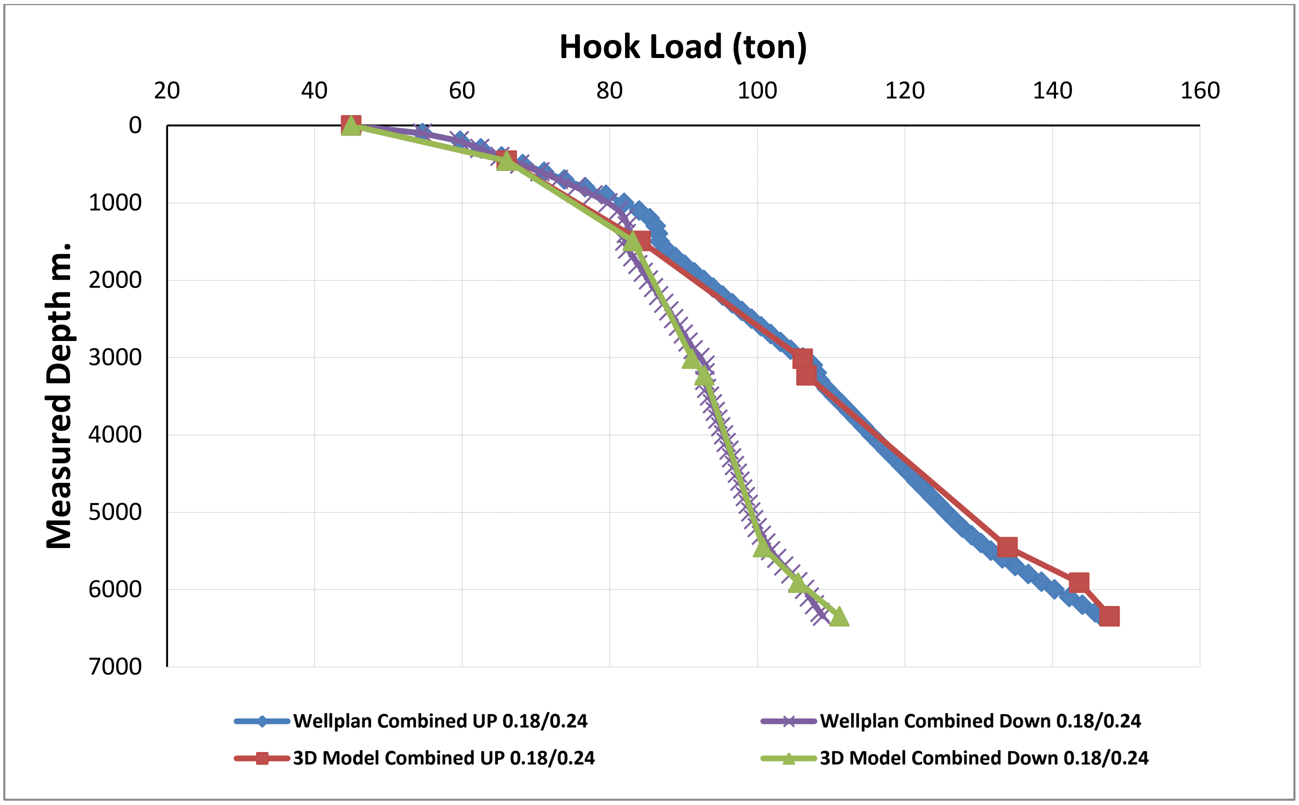

Figure 20: Comparison between 3D model simulator hook loads and Wellplan 5000.1- Combined Motion

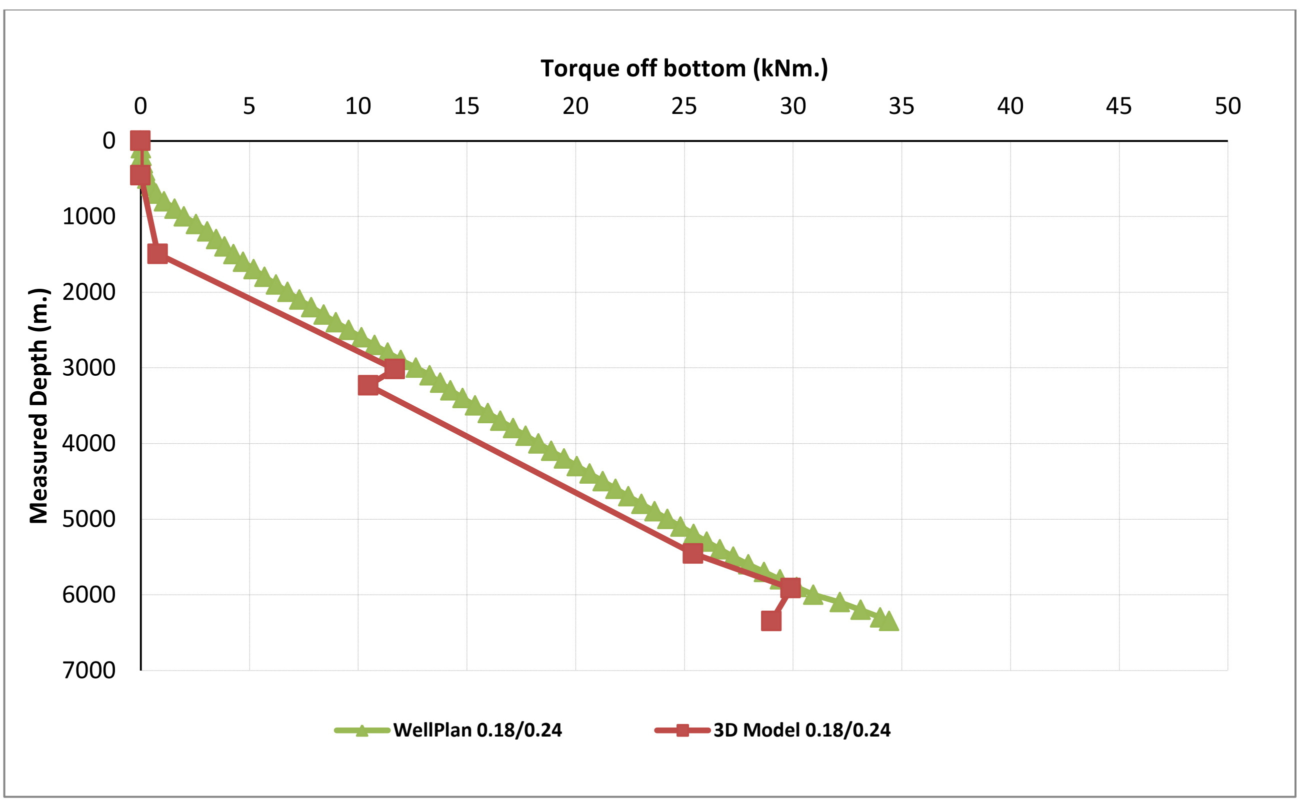

Figure 21: Comparison between3D Model simulator torque off bottom values and Wellplan simulation

Current example demonstrates comparison of torque off bottom predictions. The torque off bottom plot, Figure 21, for the comparison of the model prediction versus Wellplan 5000.1 is shown. The analytical model, use the same friction factor 0.18/0.24, for torque off bottom calculation as well. And it is required to use tool joint radius in torque off bottom equation[11].While the tool joint size was unspecified, 0.057m has been added to the drillstring body.
Again the main discrepancy happens at the well bottom. The maximum difference is approximately 5 kNm. Due to the limited number of calculated points of torque off bottom values, we can observe such sharp curve profile in the model comparing with smooth Wellplan. Such curve profile also may be explained by the "Capstan effect" which is included in to the model[11, 20].The complete solution which has more thorough application would better describe the torque prediction in current case.
The analytical model has an application for calculation torque off bottom during combined operations as well. 3D Model simulator also includes with application. The same operation is possible in Wellplan software as well. Figure 22 demonstrates comparison of torque off bottom prediction results during the combined down motion simulated both with 3D Model simulator and Wellplan. Again there is a discrepancy observed between predictions reaching its maximum value at the well bottom.

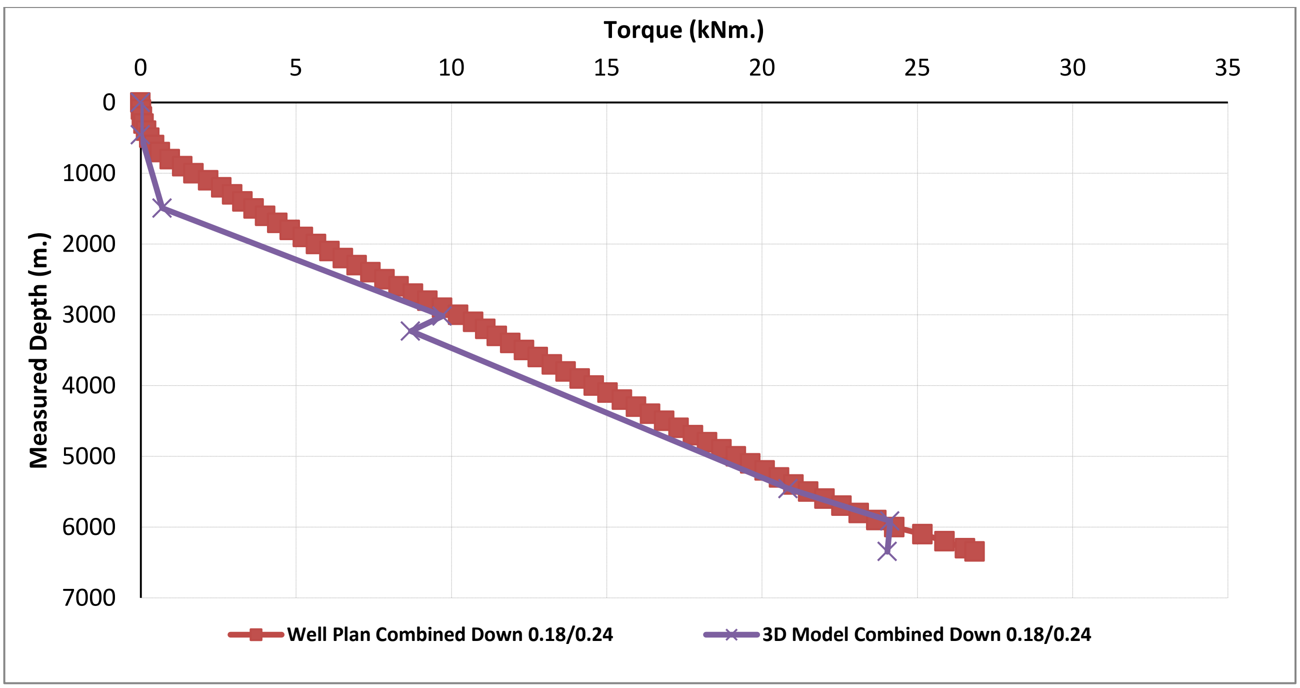

Figure 22: Comparison between3D Model simulator torque off bottom values and Wellplan simulation Combined Down motion

This example shows the comparison of actual data with the simulation during tripping in operation. Actual data has been filtered out from mud log data received from a service company. Based on the fact that all the preliminary torque and drag simulation accomplishes for the worse case scenario, by using 0.25 and 0.3 friction factor for case and open hole respectively, we decided to use the same friction factor for 3D Model simulator as well.

The actual measurements overlap quite well with both the analytical model and both Wellplan versions till the 3000 m M.D. Below this depth the actual data shows high results. High indication of measured hook loads could be caused by the fact that during the tripping-in operation, the drillstring bottom is in compression while the rest of the string is in tension. There is a zone where drillstring is switching from a tension to a compression condition. Over this transition interval, surface contact could be reduced as the pipe is neither in low side nor high side and so called pseudo-catenary well profile is forming[1,21]. This effect reduces friction along the wellbore through this interval and as a result causes high weight indication on hook load. The analytical model and Wellplan having a soft string assumption cannot take into account this and therefore have a tendency to give overestimated values, i.e. shows less hook load weight than an actual measurement during tripping in operation.

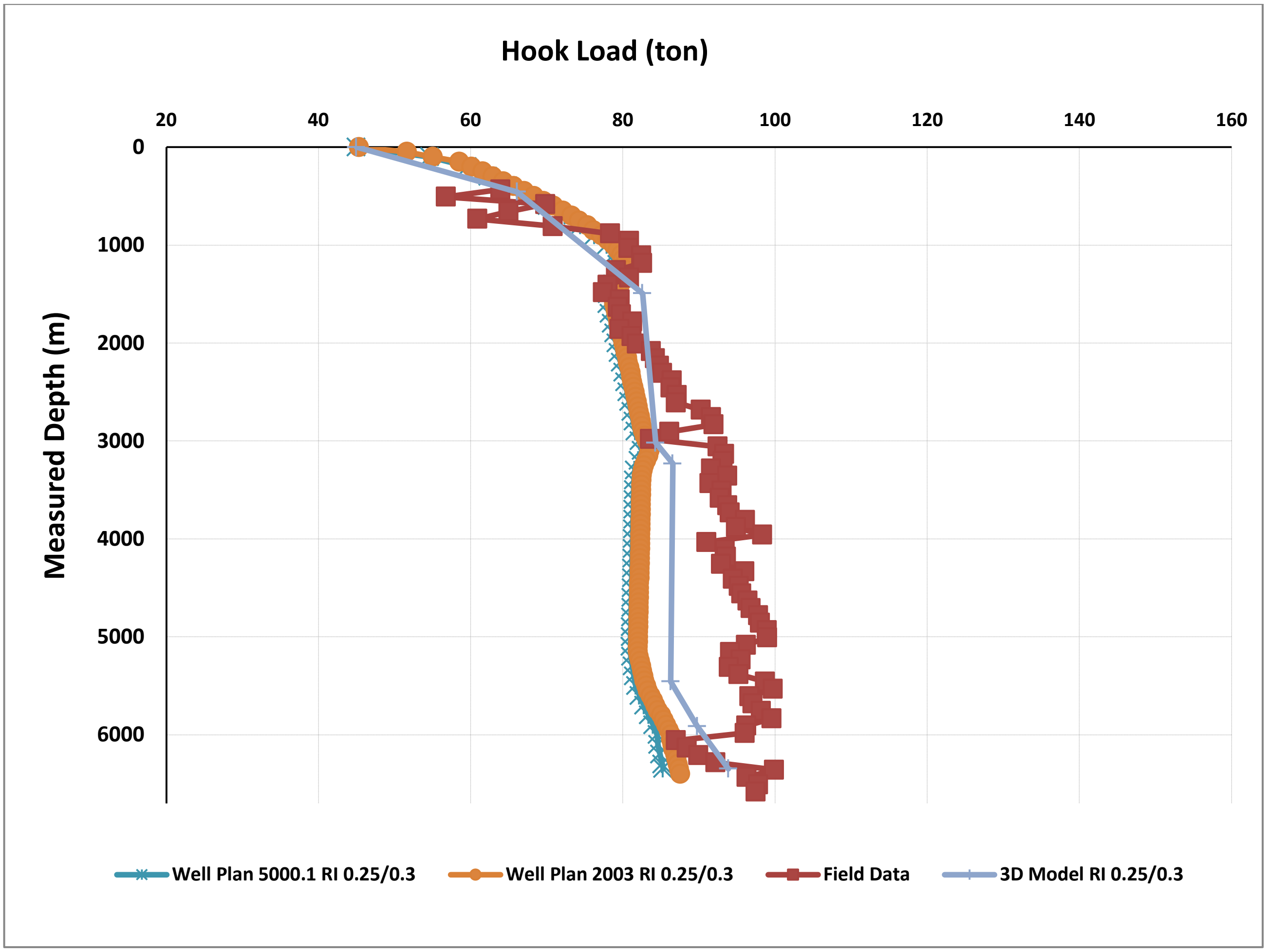

Figure 23: Comparison between field data, 3D Model and Wellplan 5000.1,2003 simulation for hook load weight prediction for tripping in operation 0.25/0.3

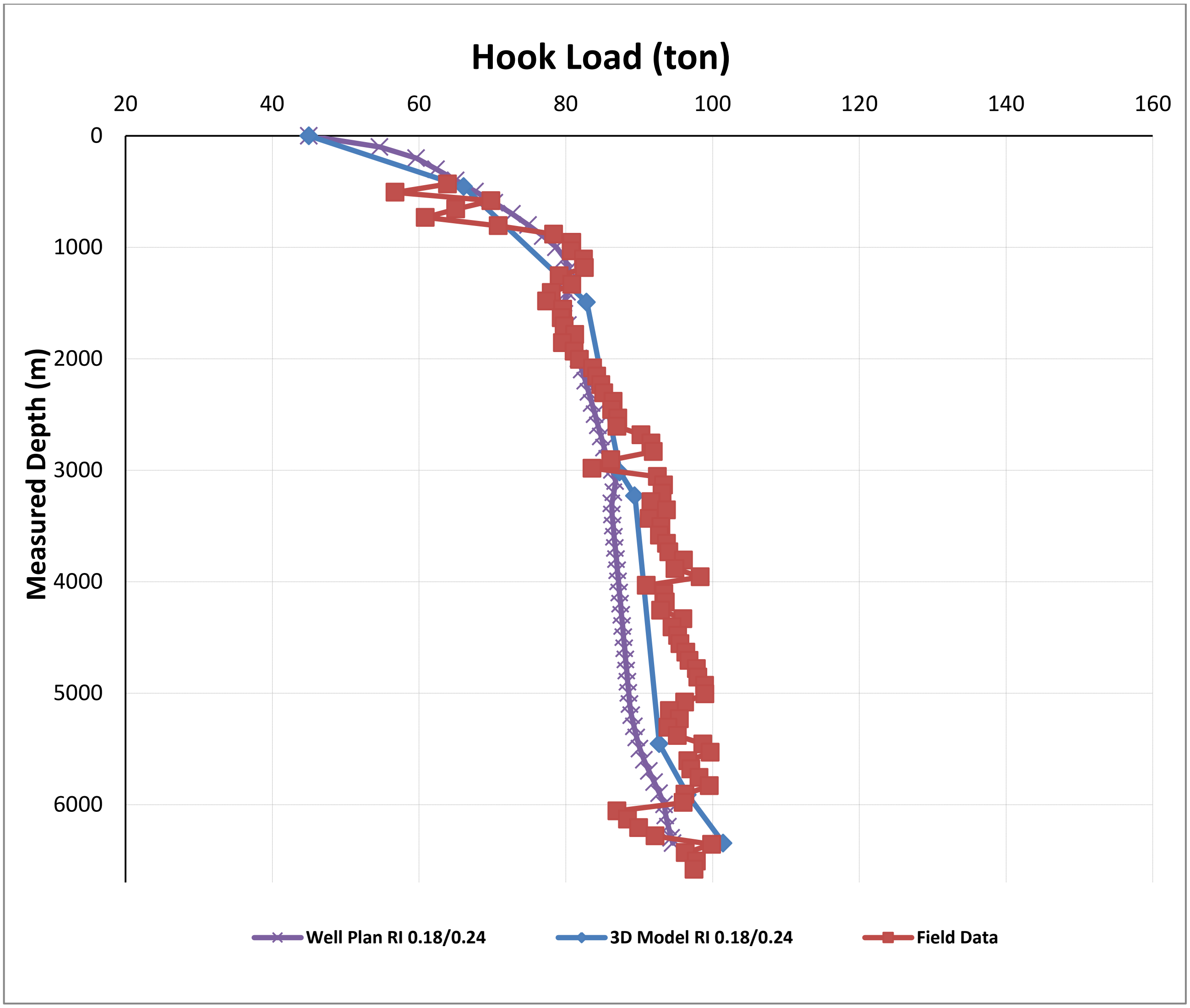

Figure 24: Comparison between field data, 3D Model and Wellplan 5000.1,2003 simulation for hook load weight prediction for tripping in operation0.18/0.24

Current comparison is done with application of 0.18/0.24 friction factor in order to better estimate the simulated results with the actual measurement. Figure 24, the analytical model gives relatively closer results with actual measurements over 2000 and 6000 depth. At the very bottom, the actual data decreases and overlaps better with Wellplan. Such sudden decrease of actual measurements could be due to the poor hole cleaning, tight hole and etc. which the analytical model cannot take into account.

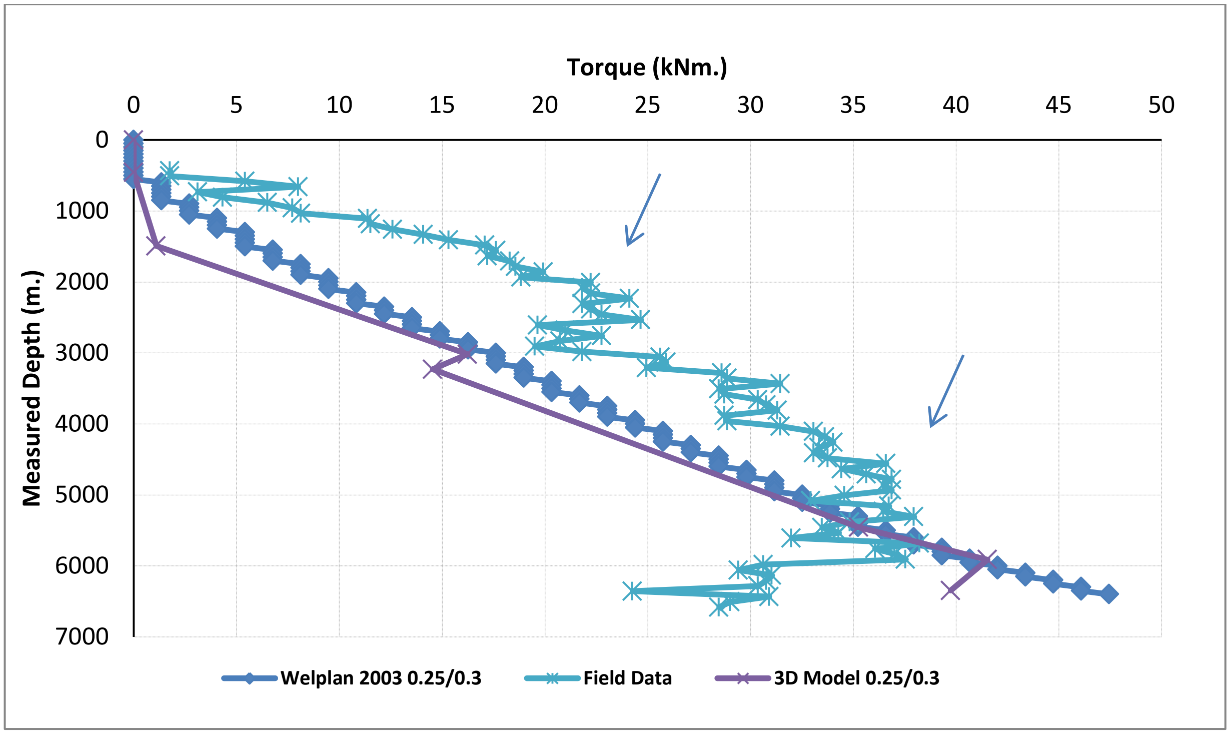

Figure 24: Comparison between field data, 3D Model and Wellplan 5000.1,2003 simulation for torque off bottom prediction 0.18/0.24

Figure 25 compares measured and simulated surface torque with bit off bottom. The discrepancies between analytical solutions and actual measurements could be considered as a big. It is always quite challenging to interpret the torque values, as the actual data very sensitive to many factors and usually has such high fluctuation. Measured torque off bottom values, show high results than both Wellplan 2003and 3D Model prediction. Even slight change in the actual wellbore diameters due to the poor hole cleaning or wellbore instability has an influence on the surface contact between wellbore and drillstring. To take into account a contact surface effect, it is required to know the hole and pipe diameter at each measured depth to be able to integrate a correction factor to the model by multiplying at friction coefficient[3].The actual torque curve profile in the current case rather challenging and without introduction extra correlation factors in the model would be impossible to predict.

5.4 Oseberg Well Information

The next well which is used in the current master thesis was drilled in Oseberg field. Oseberg is an oil field with gas cap. The field is located in the northern part of the North Sea. The water depth in the area is about 100 meter[26]. The well name is F-9 AYT4, was drilled with 8583 m measured depth and 3106 m TVD. Water depth in that particular area is 101 m. Mud weight used for 8 1/2" x 9 1/2" well section is 1.25 S.G. Casing shoe 9 5/8" shows is set at 7008 m.

Based on the inclination and azimuth changes versus measured depth the wellbore has been divided into the sections, Table 14.

Table 14: Well F-9 AYT4 well section

Section Type	Measured Depth	Section Length	Inc	Az.
	m.MD	m.	α(°)	φ(°)
Vertical	0	276.83	0	264
Build up with left hand side	276.83	133.08	0	264
Build up with right hand side	409.91	248.78	8	231
Build up	658.69	560.04	23.25	266
Tangential	1218.73	2134.69	60	266
Build up with left hand side	3353.42	218.23	60	266
Tangential	3571.65	481.21	68	258
Build up	4052.86	179.44	68	258
Tangential	4232.3	1283.3	80	258
Drop off with left hand side	5515.6	875	80	258
Tangential	6390.6	359.7	70	214
Build up left hand side	6750.3	433.7	70	214
Horizontal	7184	1399	90	191
Total Depth	8583		90.26	190.77

The well includes various wellbore sections including 3d dimensional wellbore changes and horizontal section. There are planned and vertical well view shown in the Figure 26 and 27 respectively.

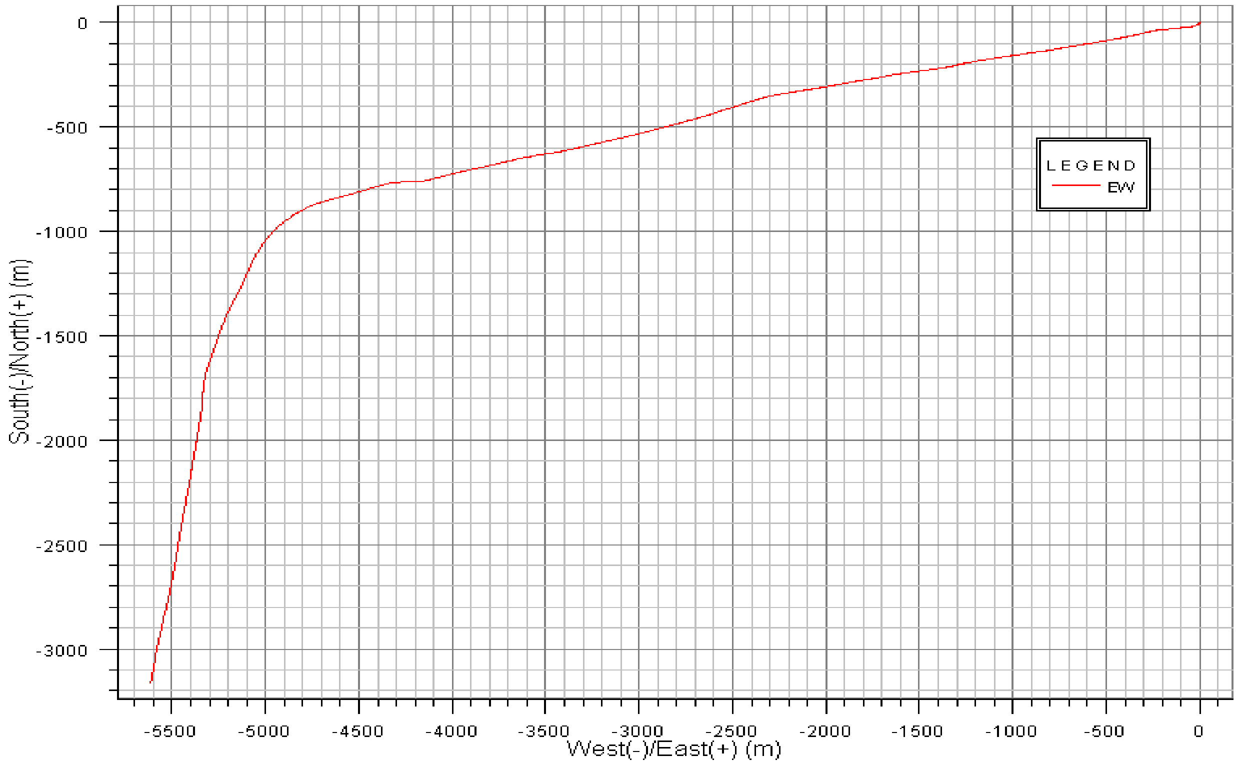

Figure 25: Planned View - Well F-9

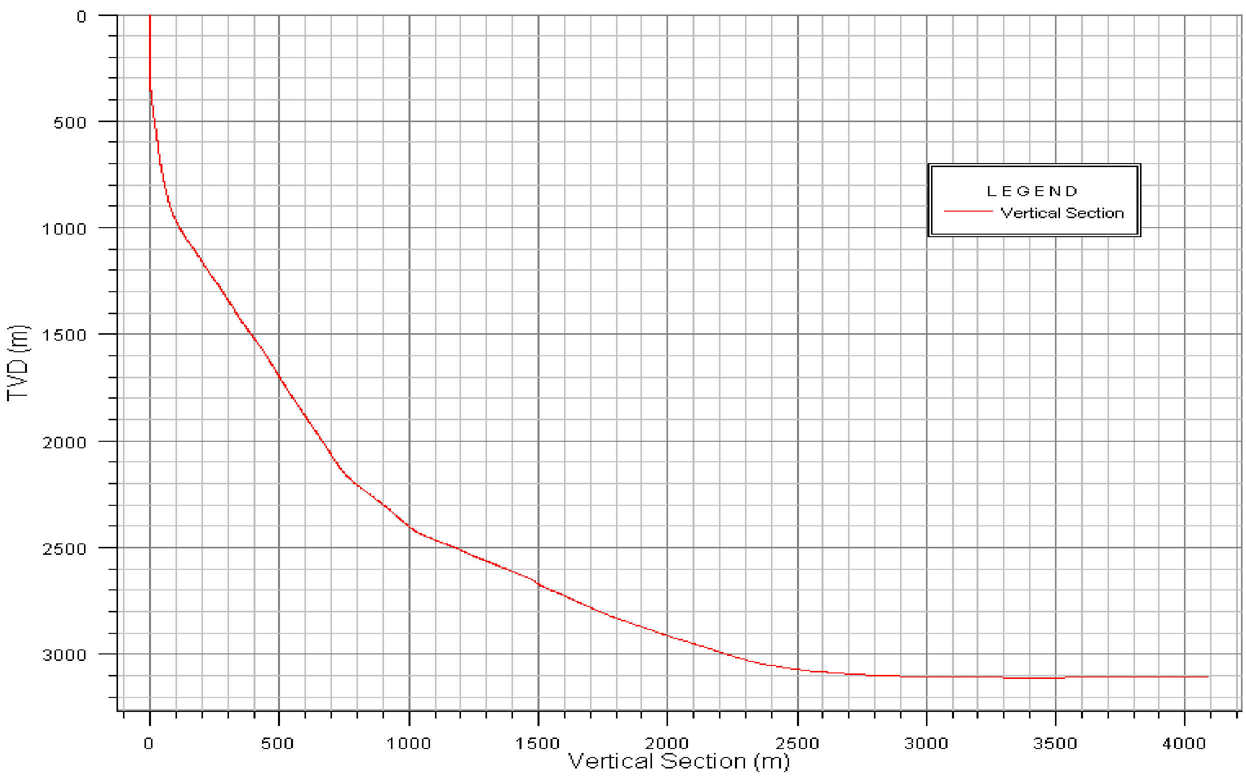

Figure 26: Vertical View - Well F-9

Appendix E includes the rest of the well information.

Based on the personal conversation with industry person, the friction factors that are using in Oseberg field during the planning phase are the following:

- Open Hole 0.25
- Cases Hole 0.20-0.22

However from the future received data we could see that the company used diverse friction factor range to fit actual measurements (Appendix E). It means that current well or in general the field has a rather complex friction factor application. But for the sake of simplicity and having a strict approach regarding the friction factor calibration, we apply constant 0.18/0.24 friction factor in all the following calculations both for 3D model and Wellplan software.

5.4.1 Results and Discussions- F-9

There is a comparison of hook load weight simulated with 3D Model and Wellplan. The static–rotating off bottom values has a good match. Tripping in and out values have overlapping trends in an upper section of the wellbore. Closer to the drillstring end the discrepancy is getting bigger. The application end condition or so called the complete solution of the analytical model could be applied in order to better describe hook load weight during the tripping operations in the last sections. As it was stated earlier, the master thesis has a strategy to evaluate the model comparing it with not Wellplan, but rather with the field measurements. Therefore, all the acquired analytical model predictions will not be accepted as wrong. The proper interpretation and evaluation will be determined by comparison the predicted values with actual measurements.

Wellplan simulation results again have quite high drag indication closer to the well end, with a number of short curved sections.

Point A on the pick up curve describes the switching interval from horizontal to build up section when the hook load due to the curved section friction contribution, starts to increase. The Wellplan prediction curve profile remains insensitive in the current situation. An application of the complete solution would give more realistic curve profile as it includes the drillstring weight term in the curved section. It is worth to mention that due the fact that the analytical model simple solution is used, it is rather challenging to distinguish the well section based on the curve profile. In addition Wellplan prediction curve profiles in most cases are also insensitive to the wellbore section.

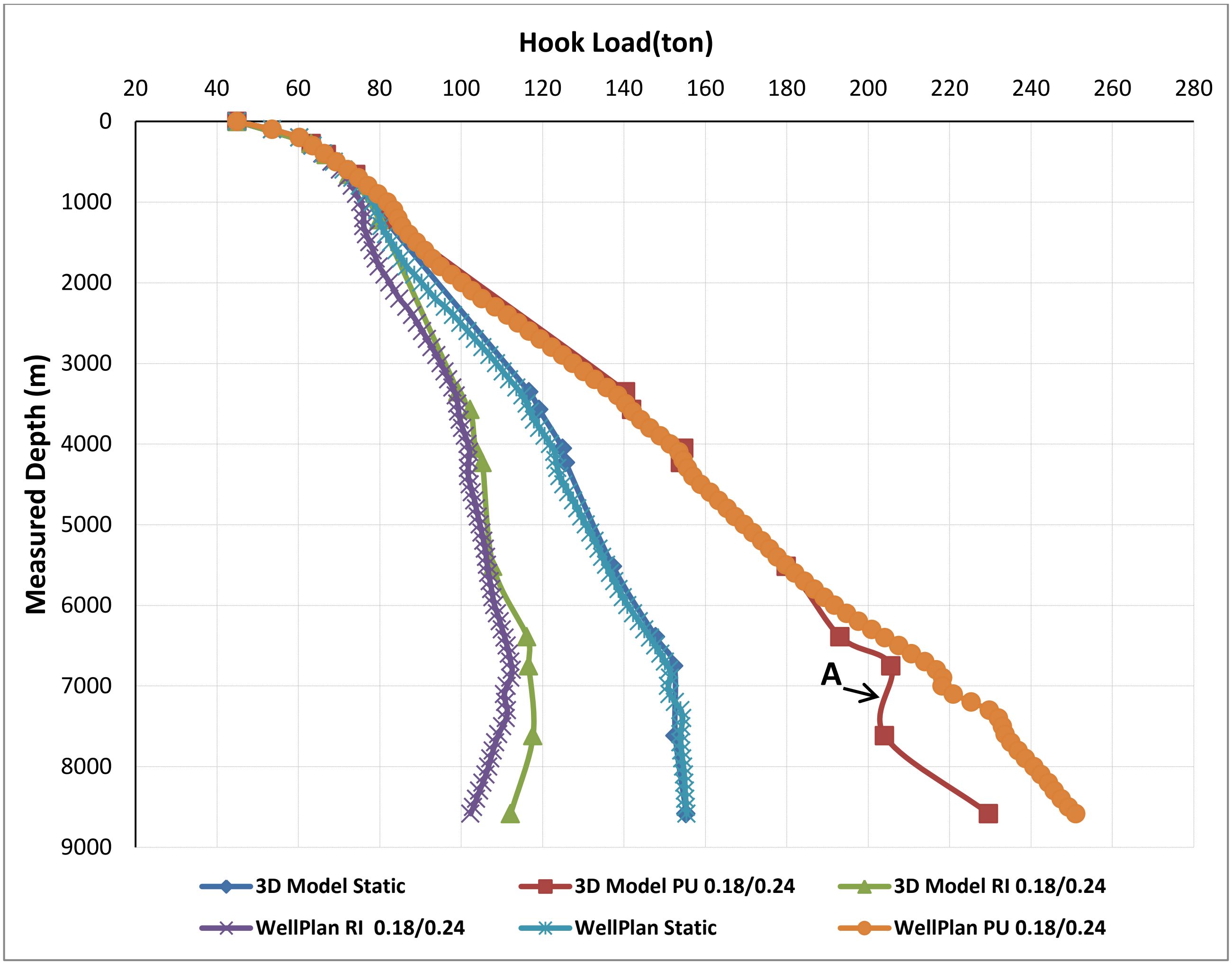

Figure 27: Comparison between 3D analytical model and Wellplan 5000.1 version –Hook Load Weight versus Measured Depth-Well F9

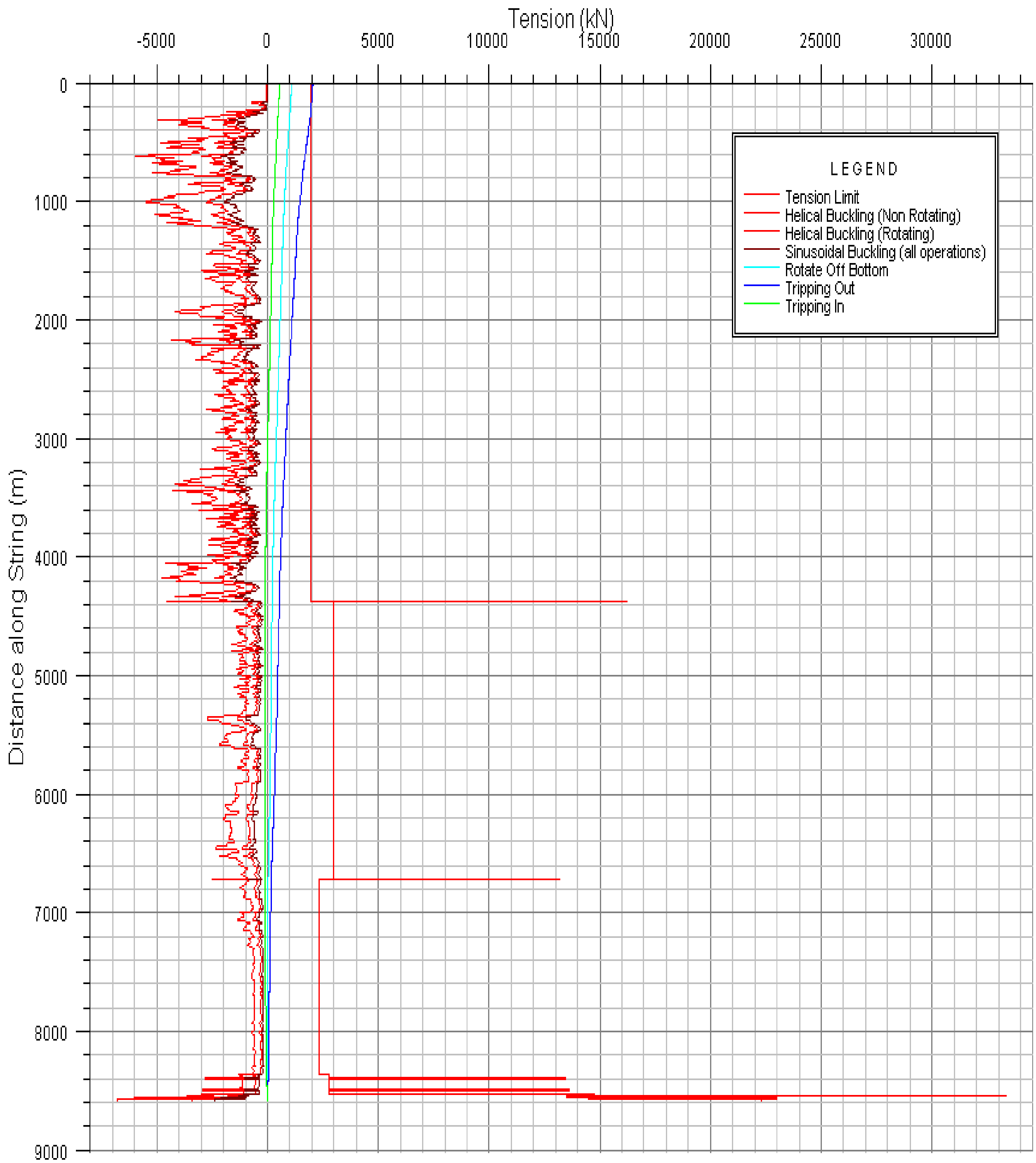

Figure 28: Effective Tension Well F-9

From test wells we have an experience that the discrepancy between Wellplan and the analytical model occurs when the effective tension in the drillstring is low and when the drillstring has a neutral point i.e. when it is partially in tension and partially in compression. Figure 29 shows the effective tension in the current well when the drillstring is at its total depth. The tension value is quite high during the pick up operation. But during tripping in operation the drillstring is switching from tension to compress mode at the 3100 m MD.

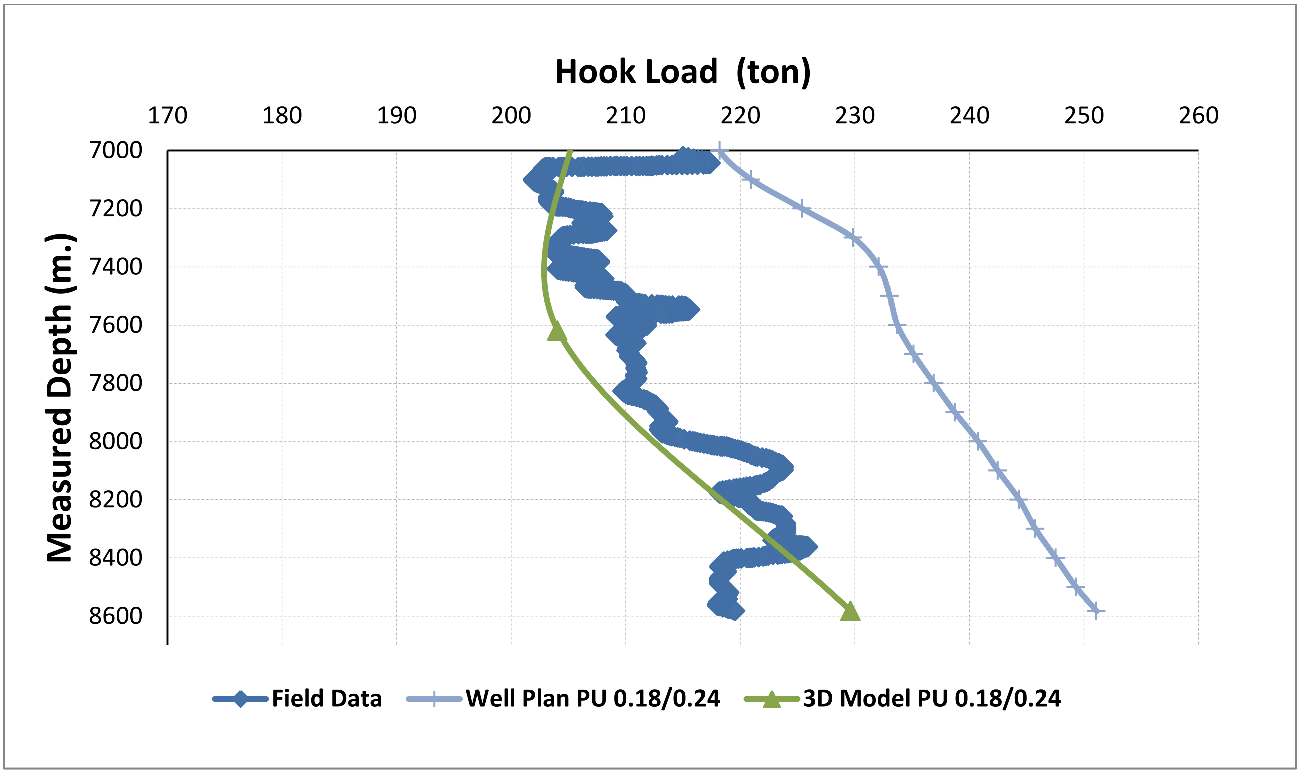

Figure 29: Comparison between field data, 3D Model and Wellplan simulation for hook load weight prediction for tripping out operation0.18/0.24

This Figure 30 demonstrates the application of the model for tripping the drillstring out and comparison it with field measurements and Wellplan prediction. The analytical model gives better match with actual measured data over the entire 7000 m and 8600 measured interval. The Wellplan simulations results in the current case quite shifter on the right site, give overestimation more than 15 ton in some points. The field data has a sharp right hand shift on the 7000 meter towards the Wellplan prediction.

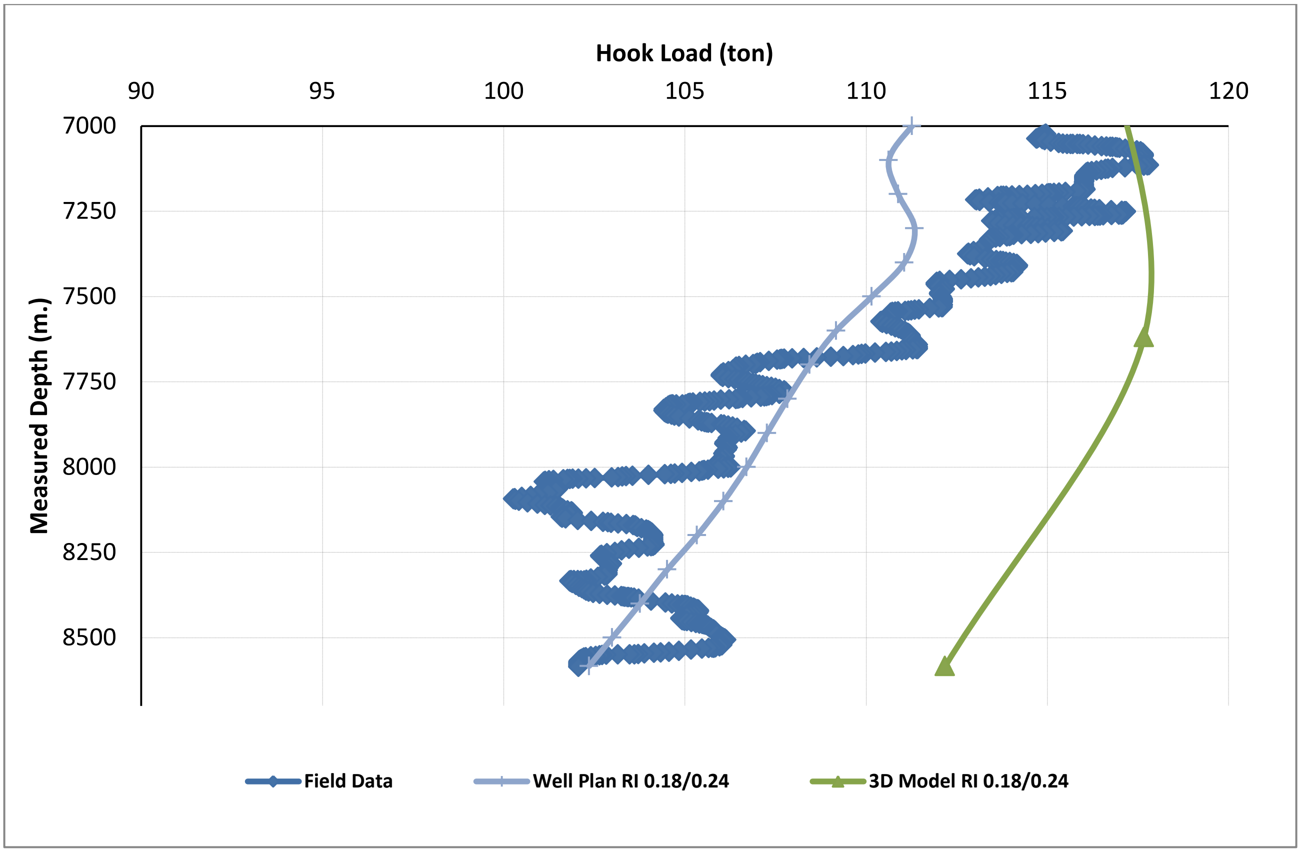

Figure 30: Comparison between field data, 3D Model and Wellplan simulation for hook load weight prediction for tripping in operation0.18/0.24

Comparison of hook load weight prediction for tripping in operation shows that Wellplan better matches with actual data. Figure 31, in the upper zone of the measurements gets closer to the model. Based on the effective tension plot, we may conclude that the analytical model simple solution does not work properly due to the drillstring tension and compression modes. The analytical model drillstring end condition could be applied to remove the current discrepancy.

If we agree on the fact that during the comparison of the analytical model with actual measurements, it is acceptable to use high friction factor because of the fact that the analytical model do not take into account tortuosity and dogleg, then the calibrated friction factor shown in Figure 32 may be applied. Application of high friction factor gives better results to match with the measurements.

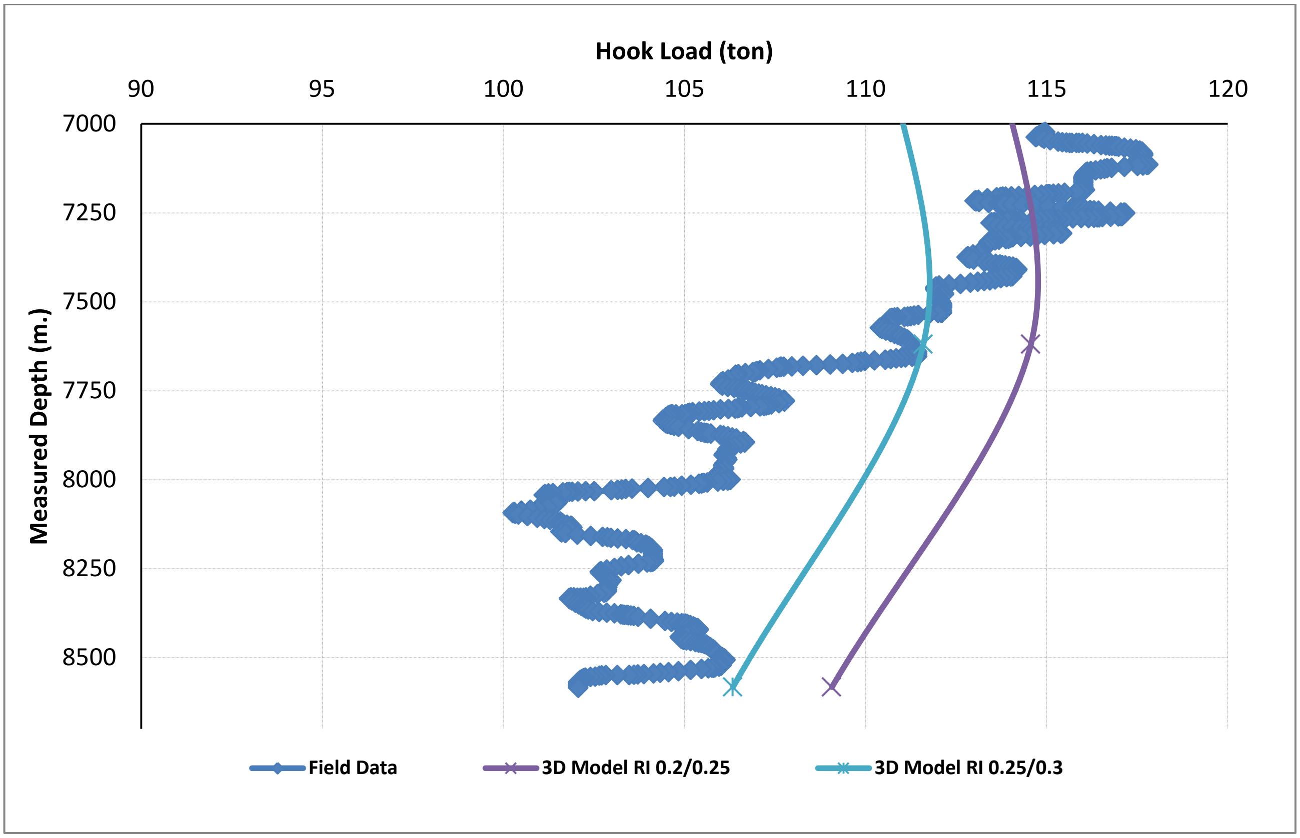

Figure 31: Comparison between field data, 3D Model and Wellplan simulation for hook load weight prediction for tripping in operation0.2/0.25 vs 0.25/0.3

As it was mentioned earlier in the thesis, for a quality control of the field data, the tripping data must be compared with static weight of the drillstring. Therefore static weight is also very important value which must be calculated during the planning phase and measured in a field. The static weight must be measured when no friction is applied to the drillstring movement. Figure 33 shows that the analytical model is slightly closer to the actual data which has high fluctuation. However, it must be mentioned that Wellplan static curve profile match better with actual, even though it's shifted more. The analytical model insensitiveness to the well sections and not repetitive behavior with actual and Wellplan simulation may occur due to the wellbore section simplification which is required before its application.

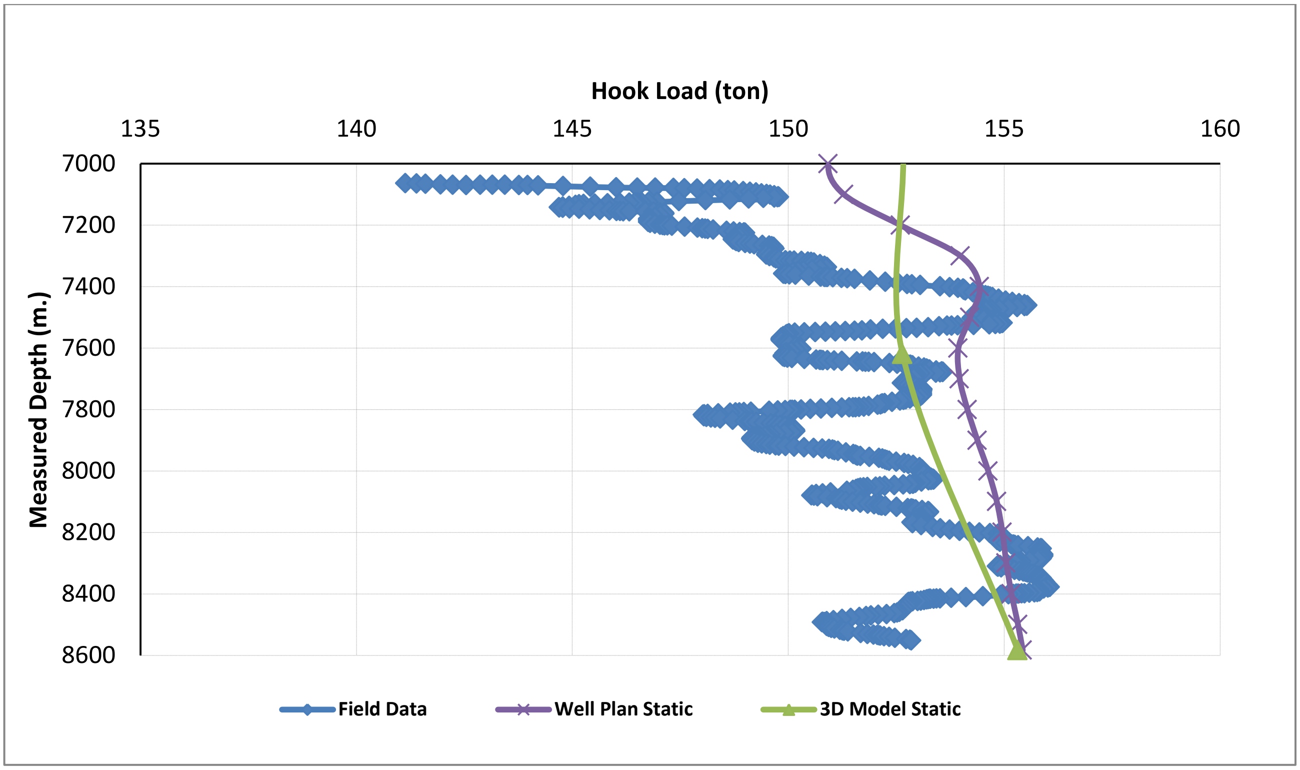

Figure 32: Comparison between field data, 3D Model and Wellplan simulation for hook load weight prediction for rotating off bottom operation

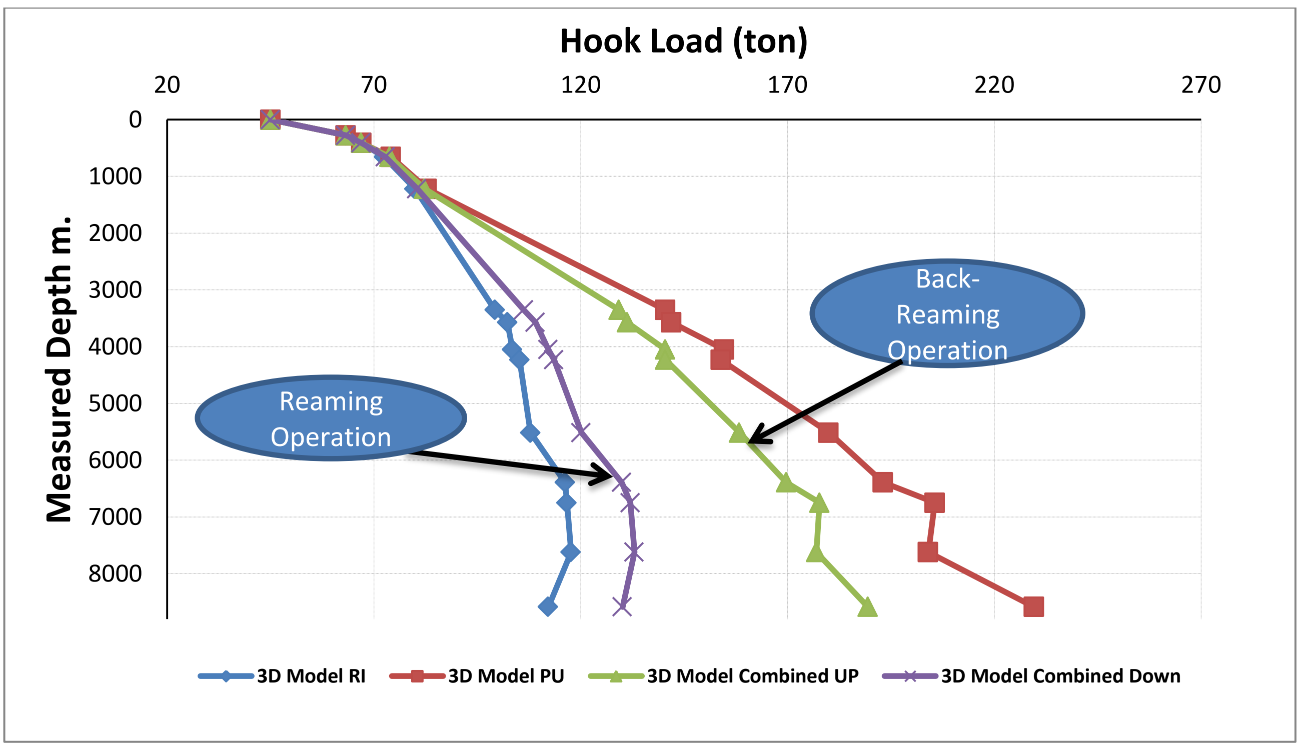

Figure 33: Effect of pipe rotation on the hook load weight while the tripping in and out operation-F9

The Figure 34, once again demonstrates an application of the analytical model for the combined up and down motion. During combined operation tripping in/out and rotary speed are 0.3 m/s and 60rpm respectively. The hook load values change with combined up and down motion for 41 ton and 8 ton respectively.

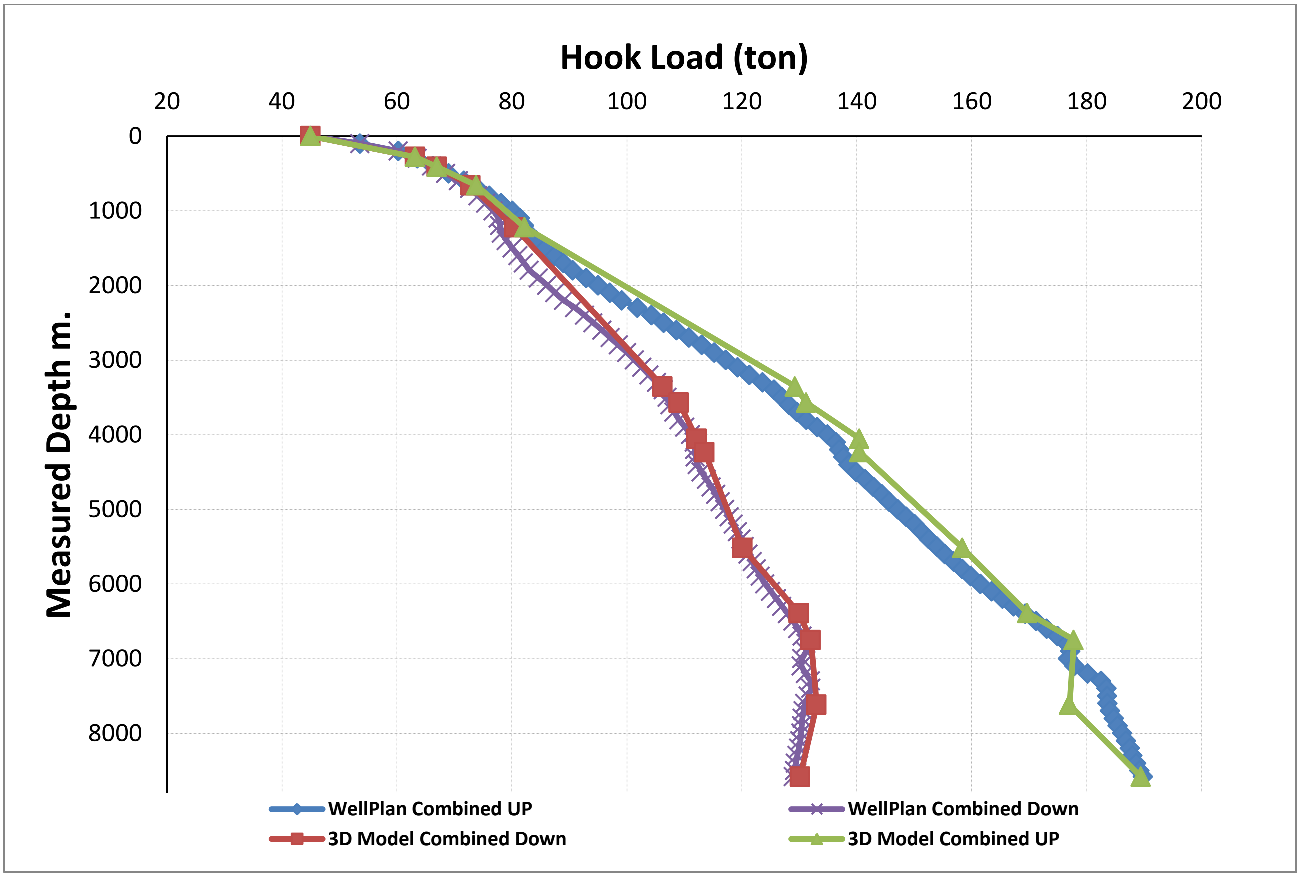

Figure 34: Comparison between 3D model simulator hook loads and Wellplan 5000.1- Combined Motion-F9

During the combined operations Wellplan and 3D Model simulator prediction has good match, Figure 35. Rotation applied to the drill string reduces axial forces and as the result the model gets less sensitive to the wellbore friction.

Comparison of surface torque off bottom prediction is shown in the Figure 36. There are a good match between Wellplan and the analytical model. Sharp end curve behavior of the analytical model is due to the "Capstan effect"[11, 20].

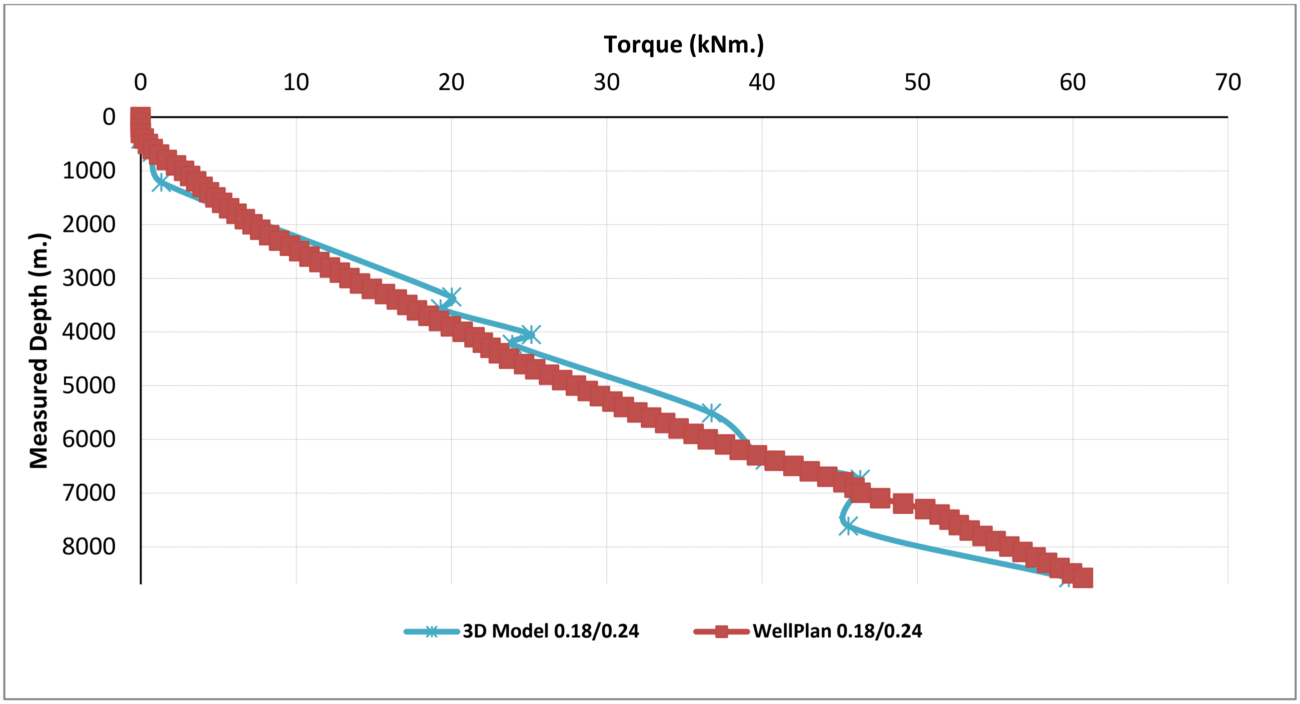

Figure 35: Comparison between 3D Model and Wellplan simulation for torque off bottom prediction 0.18/0.24

Appendix E includes figures which show the comparison between torque off bottom values simulated with 3D Model and Well plan for combined up and down motions.

5.5 Real Well 2 Information

Real Well 2 has 4610 meter measured and 3012 m TVD. Casing shoe depth is at 3518 meter. 8 ½" open hole section length 1092 meters. Drilling mud weight is 1.47 S.G. Drillstring/BHA configurations and well section information is included in Appendix F. Figure 37 shows Real Well 2 vertical view.

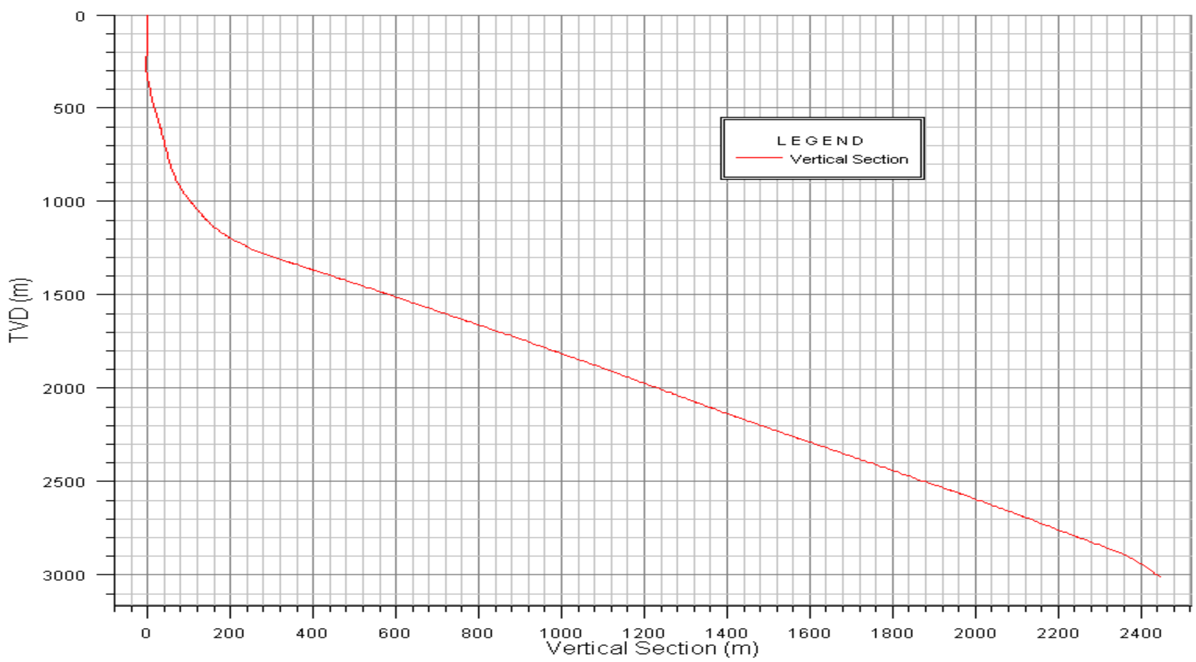

Figure 36: Vertical view – Real Well 2

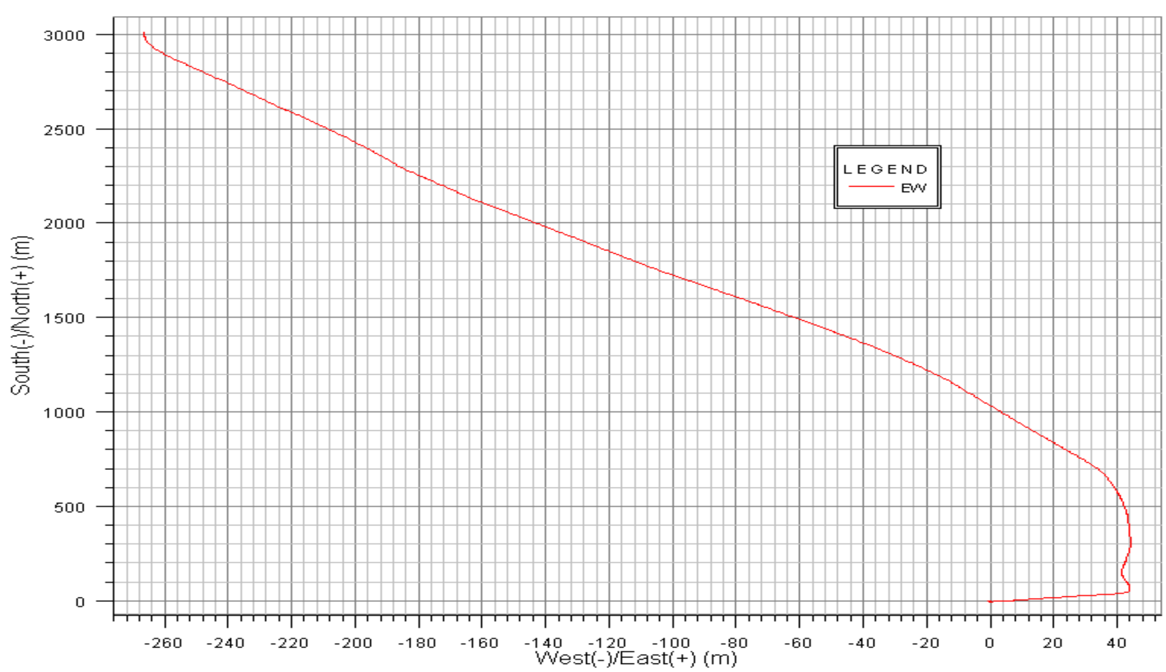

Figure 37: Planned view –Real well 2

5.5.1 Real Well 2-Results and Discussions

Figure 39 shows comparison of actual measured data with Wellplan and the analytical model. Actual data for the tripping in operation lays between Wellplan and the 3D model prediction. The rotating off bottom values better predicts with Wellplan. The difference between the analytical model and actual well data is approximately 5 tons.

Based on the previous two well comparisons, it may be concluded that with application of precise input data the static drillstring weight prediction in both Wellplan and the analytical model match good. However, the current well comparison gives the discrepancy between static plots as well. This is quite unexpected results, which could be as results of well or BHA simplification in the analytical model. The quality of the input data may also have an influence. Along with this Wellplan have more calculated points as it can be seen from the figure. This also increases an accuracy of prediction.

Hook load weight predictions for pick up operation show less value than field measurements. This could be due to the poor hole cleaning issues, when decreased wellbore profile increase friction factor and cause high hook load weight than predicted. The analytical model does not take into account local increase in the hook load. In a real wellbore with short build up/drop off radius, pipe stiffness could cause additional friction and as a result it can lead to high measured hook load values during tripping-out operation.

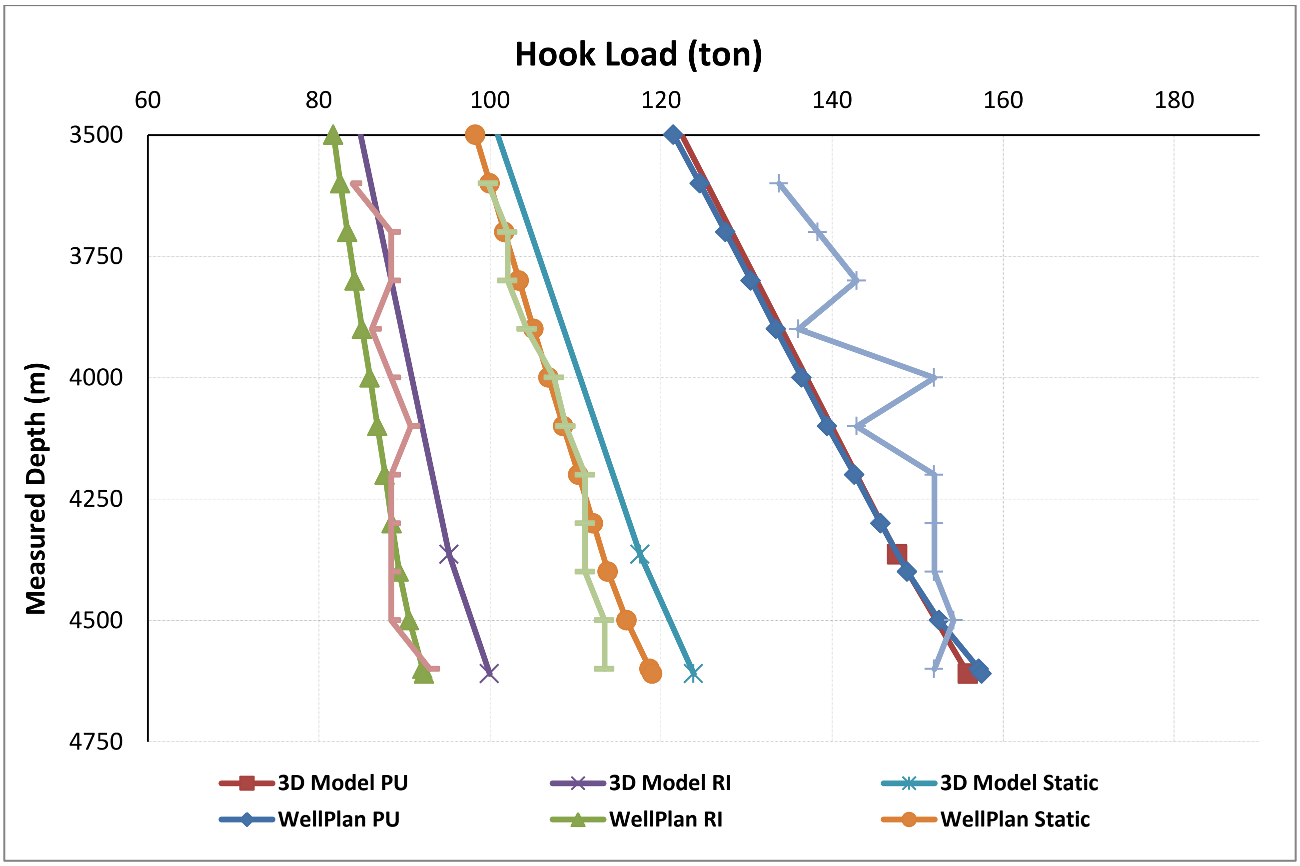

Figure 38: Comparison between field data, 3D Model and Wellplan simulation for hook load weight prediction-0.18/0.24

The actual well data contains hook load weight measurements during the reaming operation, which gives us an opportunity to evaluate and compare the analytical model during the combined motion. Figure 40 shows the measured data cross Wellplan and the 3D model prediction results. Starting from 4400 measured depth the measured depth overlaps better with the analytical model.

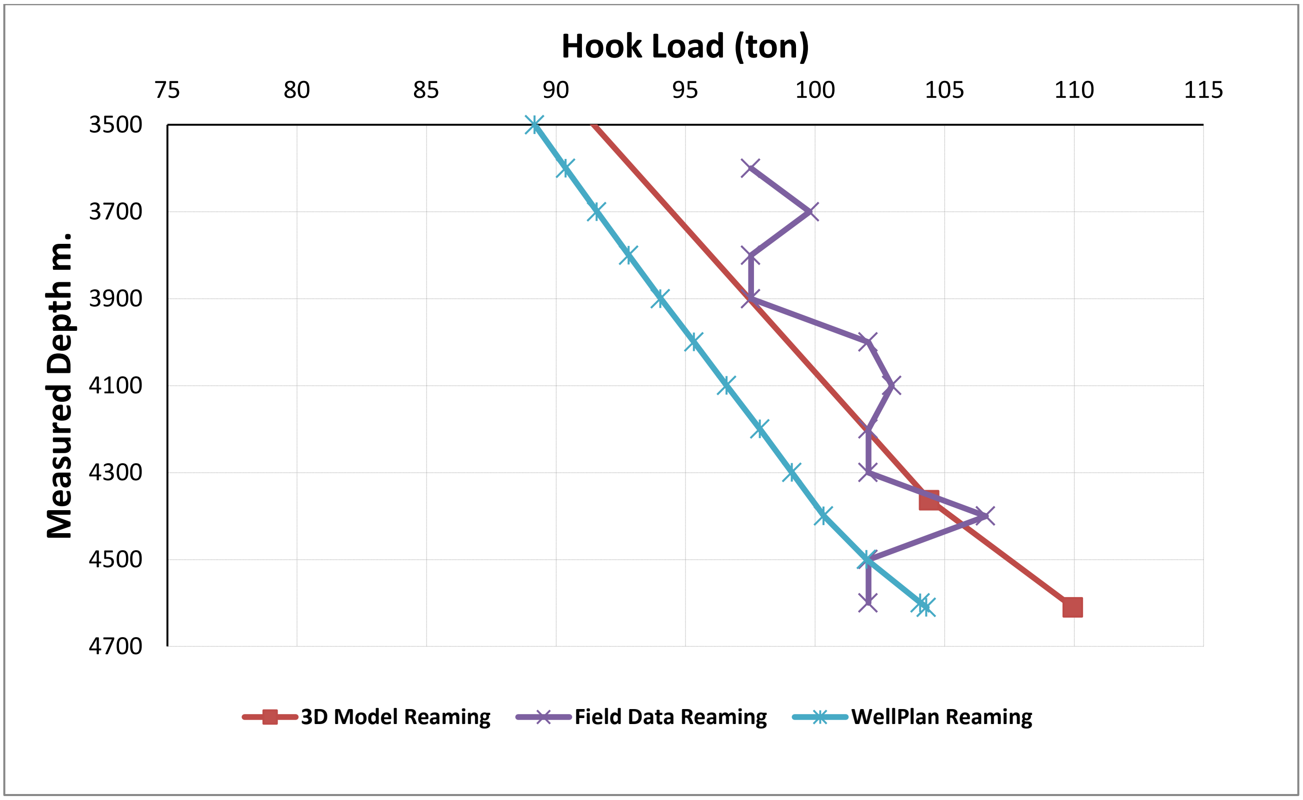

Figure 39: Comparison of actual reaming hook load weight with Wellplan and 3D model prediction

The master thesis also tries to discover the analytical model sensitivity to the changing parameters in the equation. Figure 41 shows the comparison of combined motion with different drillstring rotation speed; 60 rpm and 40 rpm. The model gives adequate behavior for the different applied drillstring rotation speed. It is sensitive to rpm.

As it can be seen from Figure 42, torque off bottom field measurement again has a fluctuation, which may be due to the dynamics such as restoring moment, tortuosity resistance , slip/stick, lateral or axial vibration[2]. The predicted torque off bottom values are less than the field measurements. The analytical model prediction relatively better matches with the actual data.

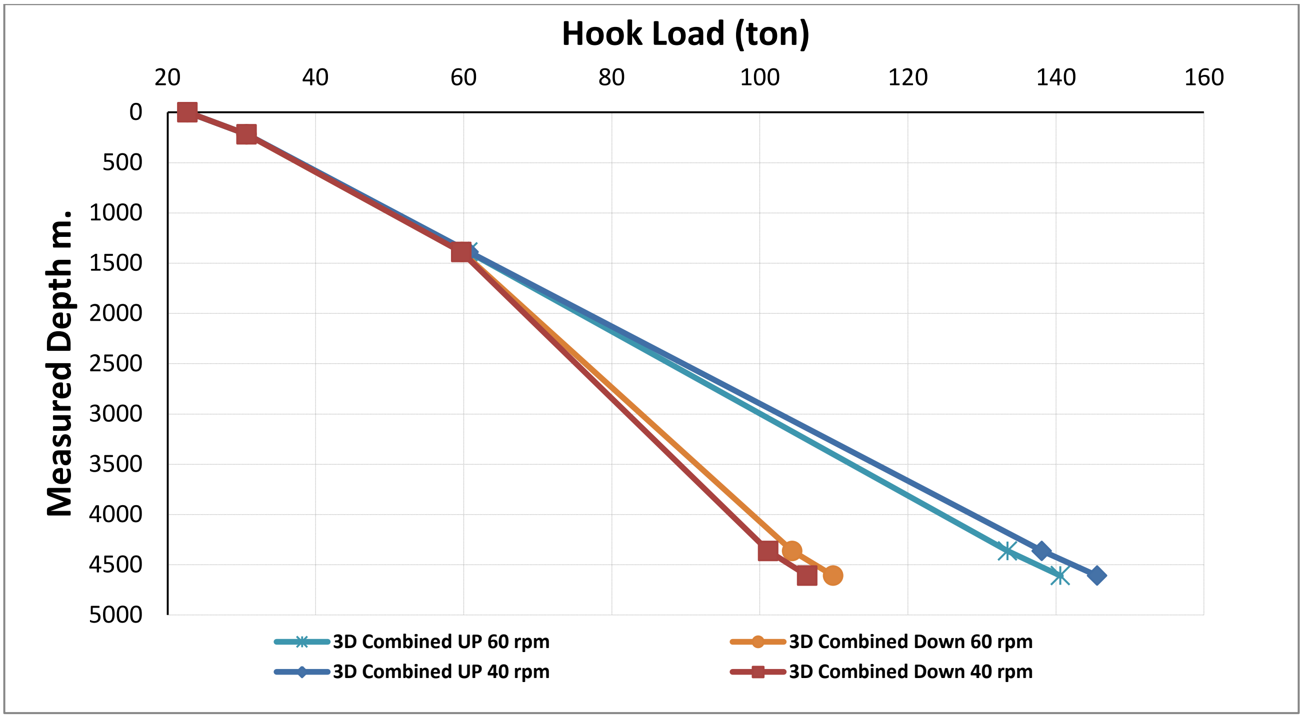

Figure 40: Comparison of the analytical combined motion application with different rpm

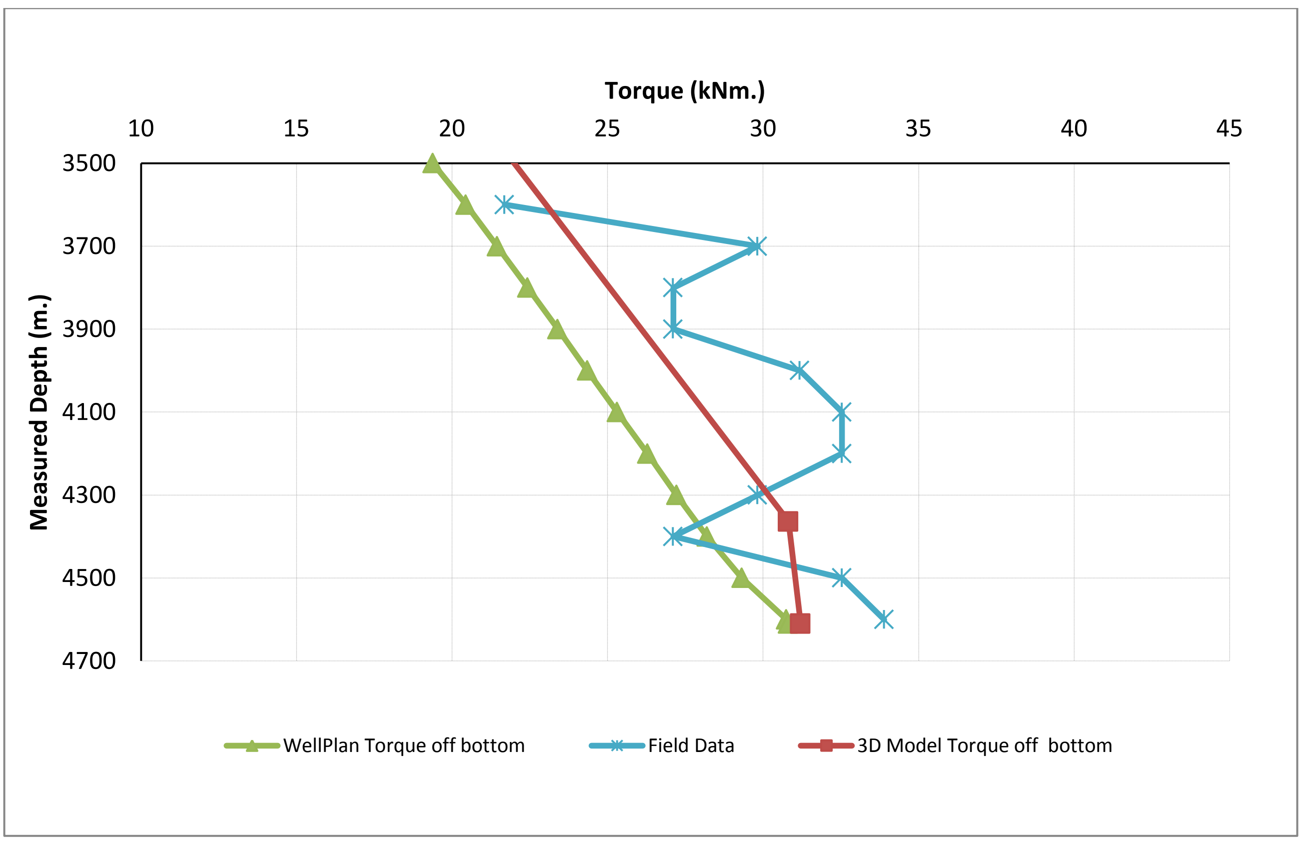

Figure 41: Comparison between field data, 3D Model and Wellplan simulation for torque off bottom prediction 0.18/0.24

5.6 Well 34/10-A-32 C Information

Well number 34/10-A-32 is also included in the master thesis with extended torque and drag analysis results for 8 ½”-9 ½” hole section. The primary objective for this well was to produce the Gulltop field optimally by only one well from the Gullfaks A platform. This is extended reach well with total measured depths equal to 9910 m. and TVD 2525 m.[8,9] Appendix G includes actual-vertical and planned views of Well 34/10-A-32 C from Wellplan 5000.1.

All the calculations are based on well surveys and input data from End of Well Report.[8,9] Based on the survey data the wellbore has been divided into the sections such as vertical, straight inclined, build up with left/right bend, drop off with left/right bend and horizontal sections. Table 14 shows all the well sections.

Table 15: Well 34/10-A-32 C well section

Sections	Drill Pipe configuration	Measured Depth MD	Inclination α(°)	Azimuth φ(°)
1.Vertical	Drill Pipe 6 7/8"	0	0	274.27
2.Build up	Drill Pipe 6 7/8"	460	0	274.27
3.Build up	Drill Pipe 6 7/8"	914.74	35.89	299.65
4.Drop	Drill Pipe 6 7/8"	1840	75.12	274.7
5.Built up	Drill Pipe 6 7/8"	1920	69.36	277.32
6.Tangential	Drill Pipe 6 7/8"	2080	80.44	272.82
7.Drop	Drill Pipe 6 7/8"	3100	80.44	272.82
	Drill Pipe 5 7/8"	3188.95	78.87	273.35
8.Tangential	Drill Pipe 5 7/8"	3260	75	275
9.Build up	Drill Pipe 5 7/8"	3770	75	275
10.Tangential	Drill Pipe 5 7/8"	3940	84	272.64
11.Drop	Drill Pipe 5 7/8"	5500	84	272.64
12.Build up	Drill Pipe 5 7/8"	5740	81.81	273.37
13.Tangential	Drill Pipe 5 7/8"	5850	84	272
14.Drop	Drill Pipe 5 7/8"	7355	84	272
15.Build up	Drill Pipe 5 7/8"	7474.19	81.21	279.39
16.Drop	Drill Pipe 5 7/8"	7649.57	88.94	281.08
17.Tangential	Drill Pipe 5 7/8"	7827.61	84	270
18.Drop	Drill Pipe 5 7/8"	8353.14	84	270
19.Built up	Drill Pipe 5 7/8"	8761.65	61.35	267.53
20.Horizontal	Drill Pipe 5 7/8"	9082.85	90	268.02
21.Drop	Drill Pipe 5 7/8"	9316.73	90	268.02
	HWDP 5"	9360.66	87.29	265.61
	BHA	9521.52	84.45	267.8
	Running Depth	9595	80.93	268.02

10 ¾” liner shoe is set at 7355 m MD and the section total depth is at 9595 m MD with approximately 2240 meters of open hole interval. The detailed casing and drillstring configuration included in the Appendix G.

5.6.1 Well 34/10-A-32 C Results and discussions

The static weight must be measured when no friction is applied to the drillstring movement. The way of computing the static drillstring weight is to give zero value to the coefficient of friction in the analytical model equations (Appendix A). Figure 43 below, describes a comparison of drillstring static weight prediction and actual field measurements. Both predictions Wellplan and 3D model are right hand side shifted from the actual measurements. Wellplan shows relatively closer results. The curve profiles are very identical in both cases with field measurements.

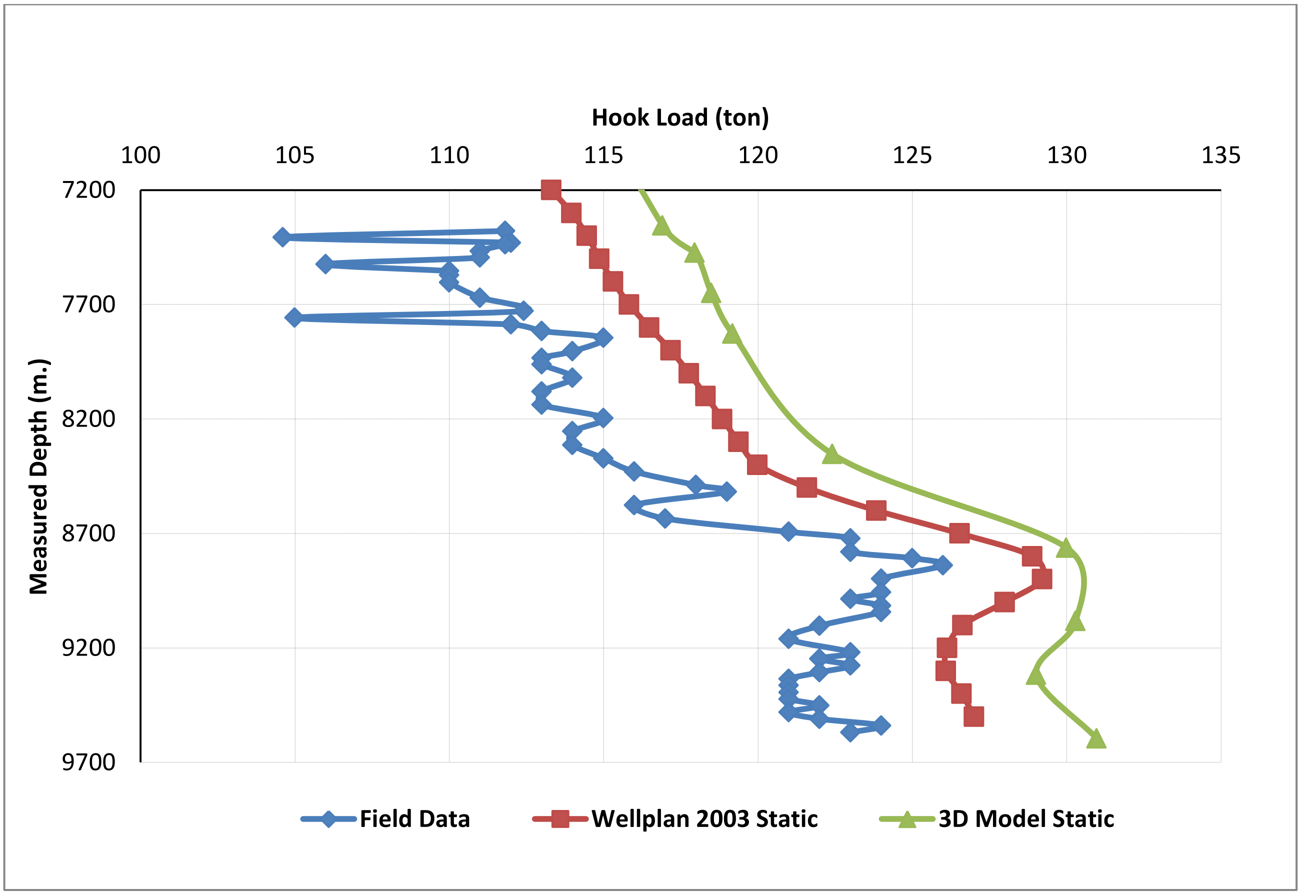

Figure 42: Comparison between field data, 3D Model and Wellplan 5000.1 simulation for hook load weight prediction –static

The application of the analytical model for the tripping out operation is shown in the Figure 44.Starting from the well bottom the analytical model is closer to the actual measurements. At the depth 8353 m MD the model has a sharp right shift deviation. Such model behavior may be due to the well section separation. This is another uncertainty which hasn’t been defined by the analytical model description. There is no strict definition regarding the wellbore separation before to use the analytical model. Actual wellbore could be separated into several so called subsections that may cause an overestimation of the hook load weight, as in this case.

It is worth to mention that, the actual data has a fluctuation seen on the curve profile. Some sudden decrease in the actual pick up, or increase during slack off operation could be explained by circulation of the cutting.

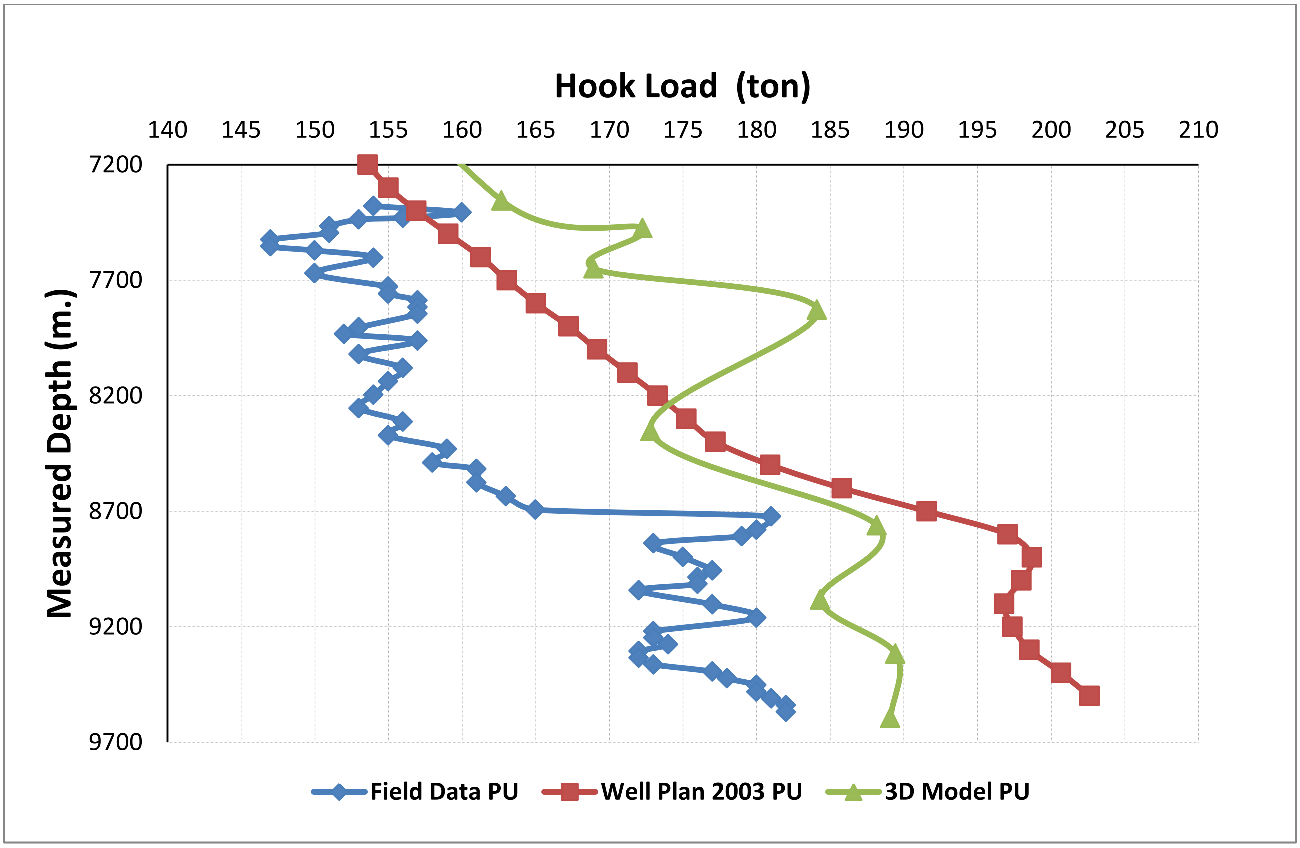

Figure 43: Comparison between field data, 3D Model and Wellplan 2003 simulation for hook load weight prediction -tripping out 0.18/0.24

An evaluation of tripping in operation has also been included. In general the tripping in operation has some complexity which should be taken into account during the comparison and evaluation of results. So called "ploughing" effect must be considered. This happens when the stiff shoe track has a tendency plough into the wellbore when passing through a build and turn section during the slack off operation[12]. Along with this, during the tripping-in operations the drillstring is filled up with drilling fluid a few times throughout the entire well interval. As a result buoyancy effect would be totally different.

Figure 45, shows the comparison of hook load weight between measured and simulated values during the tripping-in operation. The analytical model matches better with actual measurements which has high fluctuation in the given interval. The curve profiles both in Wellplan and 3D model predictions are similar with the actual. Wellplan overestimation again causes a big discrepancy with a field data.

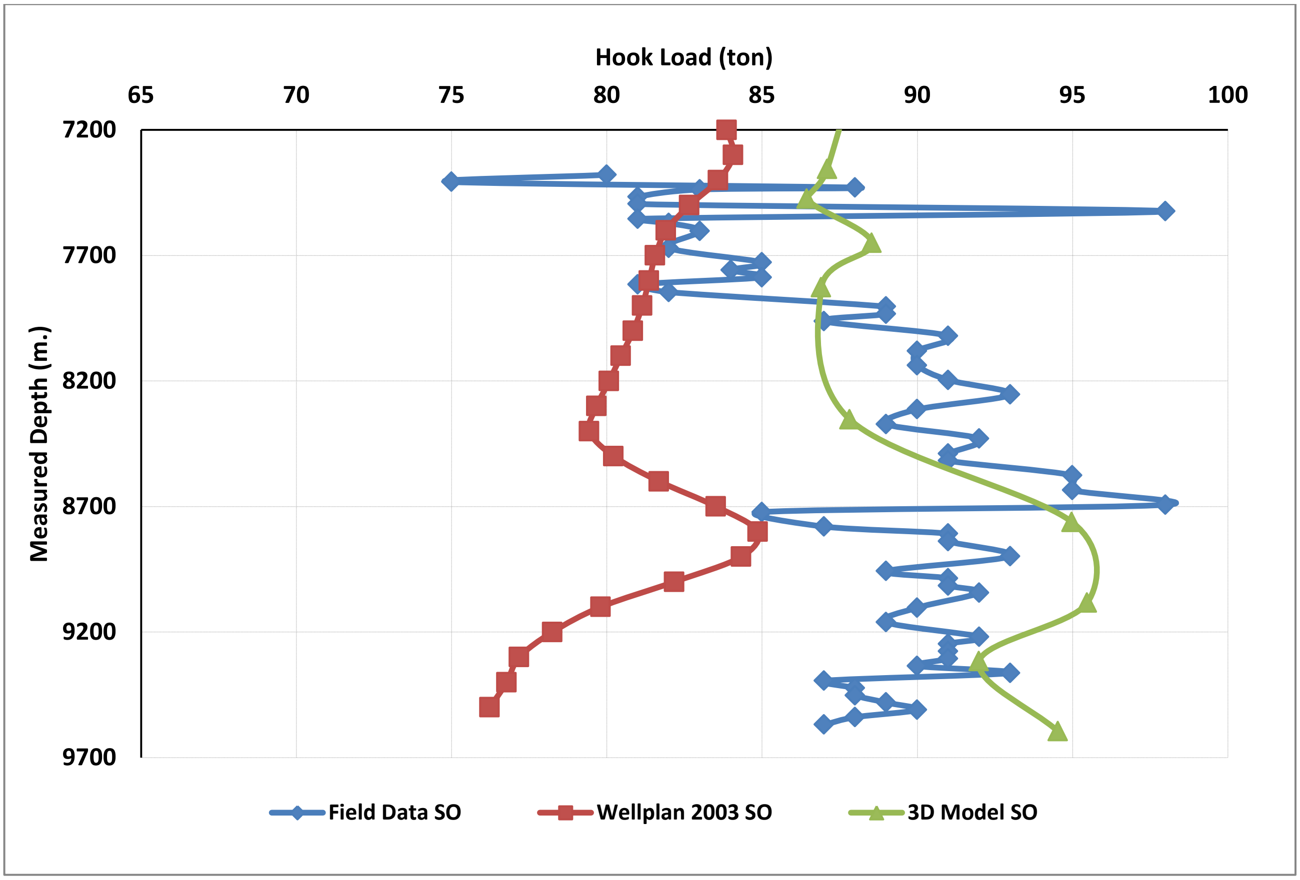

Figure 44: Comparison between field data, 3D Model and Wellplan 2003 simulation for hook load weight prediction -tripping in 0.18/0.24

Friction coefficient is a key parameter during the calculation. Usually, during the planning stage, engineers usually use friction factor having more conservative approach i.e. 0.25 for case and 0.3 for open hole. Currently, due to the increasing number of ERD well it is required to use friction coefficient which is as much realistic as possible. In many cases it is based on the previous field experience, calculated from back calculation. Back calculation must be precisely accomplished in a field in order to be able to apply it for the future wells in the same area.

It was decided to make a back calculation for the Gullfaks well for better understanding of friction behavior over the open hole section. This example tries to investigate the back calculation for the friction coefficient using Matlab application[25].Matlab script code is included in the Appendix H.

Due to the fact that real friction coefficient is quite sensitive and highly fluctuating parameter being a function of surface wall contact and hole cleaning issues; it is difficult to exactly define friction from back calculation. The available actual hook load weight measurements are only for a given well interval (7355 m. MD- 9595 m. MD). Due to the extremely time consuming of back calculation, it was required to make an assumption regarding the depth correlation of the measured data. Therefore the friction curve profile will not discussed in details, because there is a chance that the friction values will be shifted relative to the depth. The primary objective was to estimate the average value. Hook load with 40 tons is not included during the back calculations, because Matlab code and equations assumes that the total weight is distributed along the entire drill string.

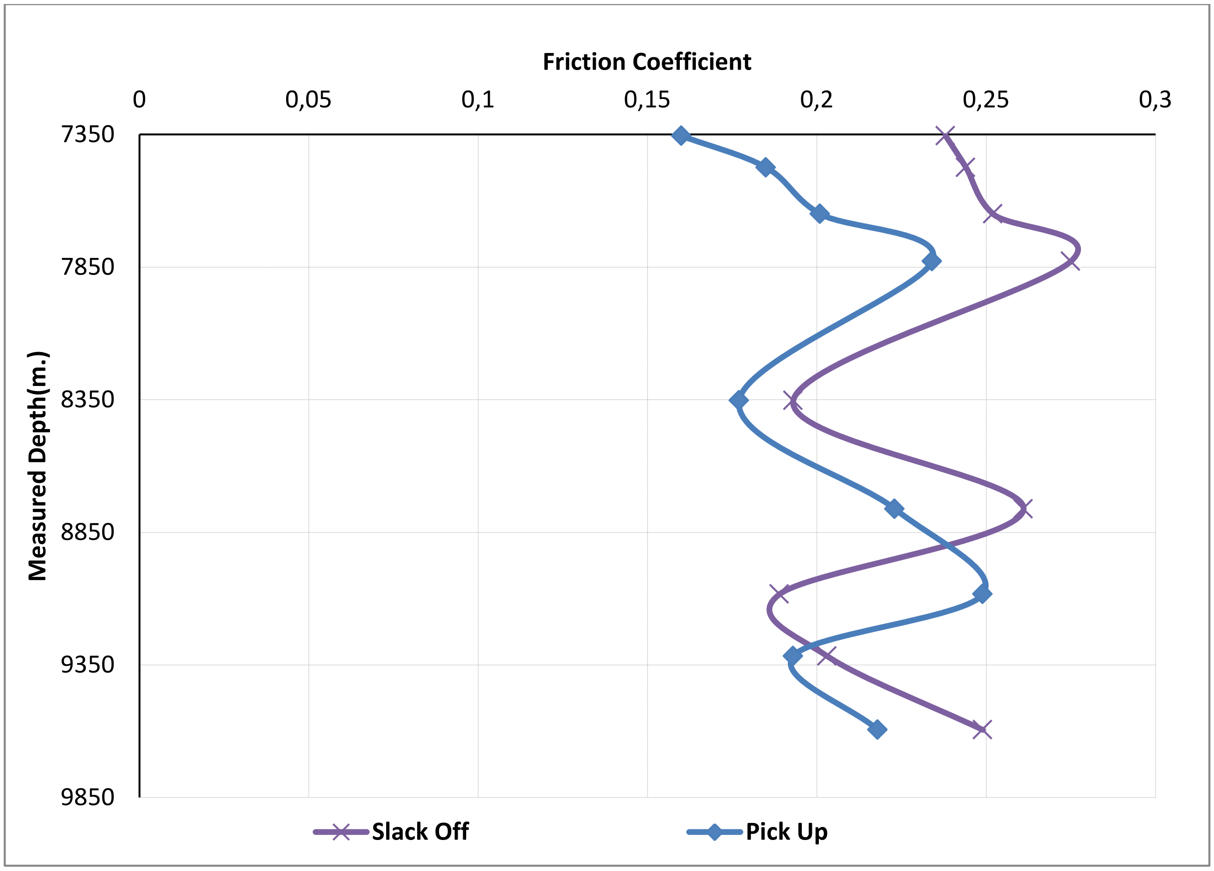

Figure 45: Friction coefficient back calculation for pick up and slack off operation

Figure 46 demonstrates the friction back calculation results. The friction coefficient for pick up operation is less than for slack off operation. An average of friction factor for tripping out is 0.20 while for tripping-in this value makes 0.23.The discrepancy may be due to the fact that the analytical model is not able to take into account the compression forces in the drillstring during slack off operation. Having a soft string assumption, the model cannot precisely describe side force effect on the drillstring. Particularly, in the build and turn section the friction coefficient may change being the resultant effect of contact surface between the borehole and the bottom hole assembles[4].The difference also may occur due to the different borehole condition between the drillstring runs. In addition, spring effect, stabbing effect and ledge effects during the tripping-in operation can cause high friction value compared with the tripping-out[2].

As a last example for the current well, surface torque off bottom simulation results and comparison is given in the Figure 47. The analytical model torque off bottom calculation uses the same friction factor that has been used for the drag simulation, i.e. 0.18 and 0.24 for case and open hole respectively. The analytical model prediction better overlaps with the field data. However in the upper section, it looks like the model starts to give a discrepancy, overlapping better this Wellplan results.

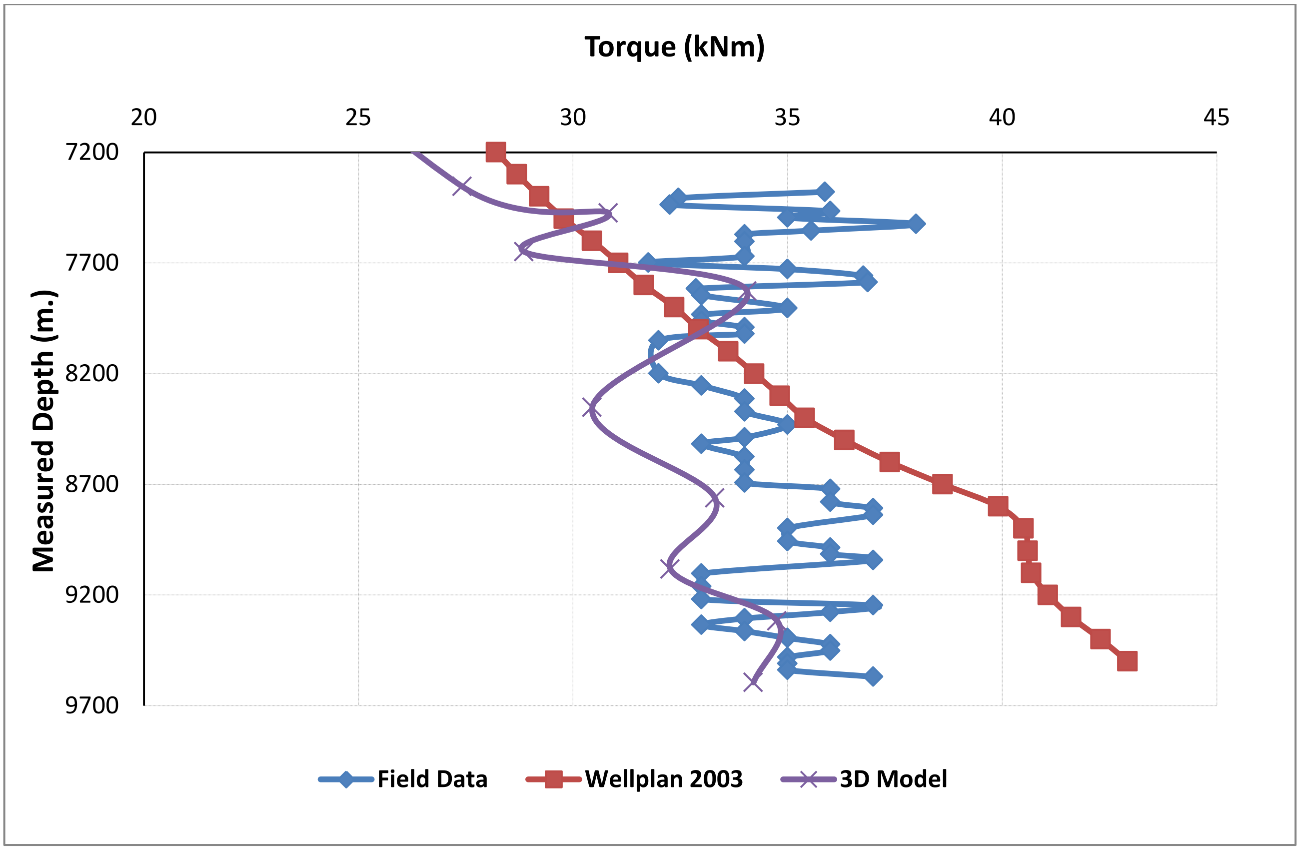

Figure 46: Comparison between field data, 3D Model and Wellplan2003 simulation for torque off bottom prediction 0.18/0.24

6. Future Work

As it was stated throughout the master thesis there are several points regarding the analytical model which needs to be further investigated in order to better evaluate a full picture. The following aspects may be proposed as a future work:

3D simulator may be further improved by introduction of the analytical model complete solution. In addition, it may also include a function which would be able to recognize exact drillstring effective tension values along the entire wellbore. And based on this analysis and applied operation in the wellbore, the simulator may determine the required equation/solution.

The well section separation based on the survey data can also be programmed. This would give a big advantage to save a time and would eliminate human involved errors. For this purpose, the wellbore tortuosity and dogleg effects on the analytical model torque and drag prediction must be further investigated. The friction factor calibration in order to take in account real wellbore irregularities and doglegs must be confirmed by number of case studies.

When the drillstring stiffness is increased the analytical model will cause an error because it is based on the soft string model assumption. In particular cases when BHA with a number of heavy components or when a casing is running, the soft string assumption may be questionable. An application of the high friction factor could compensate such stiffness in the drillstring or casing. But this is rather vague operation, which must be further studied. Field case experiments and studies as a solution can develop a table which would determine the pipe stiffness and suggest incremented friction factor correction. This will eliminate an error caused by the soft string assumption.

Ideally it would be better to apply the analytical model with actual wells data with verified data quality. That would give us more reliable result. Comprehensive evaluation, would give an opportunity to evaluate effect of other parameters on the wellbore friction behavior such as hole cleaning, viscous drag effect, tension along drillstring when pumping down the mud, pump off/on effect and etc. An ability to use the analytical model with hydraulic computations in the real time and also taking into account dynamic and vibration issues may be the next step in the torque and drag analysis.

7. Conclusion

It is difficult to give a general estimate of how good the analytical model is for the wellbore friction analysis. The precise model evaluation depends on many factors and parameters. Due to the number of uncertainties and poor quality of the received actual data the final conclusion will be done with some preservation.

Based on all the simulation and comparison included in the thesis, the following conclusion may be summarized:

1. All the predictions obtained with the analytical model gave the reasonable torque and drag results. The discrepancy acquired during the comparison of simulated hook load and torque values with the measured data was within 20%.
2. The analytical model simple solution which was the main tool in all the included calculation does not always correspondingly describes torque and drag analysis in complex wellbore profiles. The main difference occurs closer to the well bottom where the tension/compression dominance in the curved section is decreased compared to the drillstring weight. Simplified equations may be applied for predictions but based on the drillstring tension value, it can give significant errors. The analytical model is a strong function of the effective tension in the drillstring and in an ideal case the drillstring must be evaluated on the tension and compression values before application either a simple or the complete solution. The question is how precisely to distinguish the drillstring tension/compression range, in which the usage of the simple solution would be acceptable.
3. The analytical model starts to give a discrepancy with Wellplan hook load simulation during the slack off operation, when the drillstring has a neutral point i.e. the drillstring is partially in tension and partially in compression. With an application of the complete solution the discrepancy for the simplified wellbore test wells is considerably decreased.
4. Taking into account the fact that the analytical model assumes smooth wellbore profile and neglects dogleg and wellbore tortuosity, an application of slightly higher friction factor could be necessary during comparison. Otherwise, as an option it may be suggested to consider more careful wellbore profile separation.
5. Comparison with actual data shows that the soft string model (Wellplan and analytical model) gives overestimated results, i.e. gives higher and lower results during pick up and slack off operations respectively.
6. 3D Model simulator gives a valid torque and drag prediction based on the analytical model simple solution.

The analytical model full application is very time consuming, which makes it disable for using for real time analysis. Since the current master thesis did not include all the application offered by 3D analytical model, further investigation is required for comparison with a high quality actual field data.

Nomenclature

A, B	constants,
A_i, A_o	inner/ outer cross sectional pipe areas,
D	depth
d	string outer diameter
F_1	force at the bottom,
F_2	force at the top,
F_{dl}	dead line tension,
F_N	normal force,
L	pipe length,
n	flow-behavior index
N	number of drilling lines between blocks,
N_r	rotary pipe speed, rpm
K	weight term
r	pipe/connection radius,
R	radius of curvature
R_α	radius of bend in vertical plane
TOB	torque on bottom
T	torque in string,
V	velocity,
V_h	axial velocity,
V_r	tangential pipe speed
w	unit pipe weight,
W	total string weight,
WOB	weight on bottom
A	wellbore inclination, rad
β	buoyancy factor
θ	absolute change in direction, rad
μ	coefficient of friction
ρ	density
ψ	angle between axial and tangential pipe velocities, rad
ϕ	wellbore azimuth, rad

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Appendix A - 3D Analytical Model Equations

1. Drag for straight inclined wellbore section without pipe rotation

$$F_2 = F_1 + \beta \Delta L w (\cos\alpha \pm \mu \sin\alpha)$$

2. Torque for straight inclined wellbore section without axial pipe motion

$$T = \mu r \beta w \Delta L \sin\alpha$$

3. Drag for curved wellbore section without pipe rotation

$$F_2 = F_1 e^{\pm\mu|\theta_2 - \theta_1|} + \beta w \Delta L \left[\frac{\sin\alpha_2 - \sin\alpha_1}{\alpha_2 - \alpha_1} \right]$$

4. Torque for curved wellbore section without axial motion

$$T = \mu r N = \mu r F_1 |\theta_2 - \theta_1|$$

5. Drag combined axial motion and rotation for straight pipe section

$$F_2 = F_1 + \beta w \Delta L \cos\alpha \pm \mu \beta w \Delta L \sin\alpha \sin\psi$$

6. Torque combined axial motion and rotation for straight pipe section

$$T = r \mu \beta \Delta L \sin\alpha \cos\psi$$

7. Drag combined axial motion and rotation for curved pipe section

$$F_2 = F_1 + F_1 (e^{\pm\mu|\theta_2 - \theta_1|} - 1) \sin\psi + \beta w \Delta L \left[\frac{\sin\alpha_2 - \sin\alpha_1}{\alpha_2 - \alpha_1} \right]$$

8. Torque combined axial motion and rotation for curved pipe section

$$T = \mu r N = \mu r F_1 |\theta_2 - \theta_1| \cos\psi$$

$$T = \mu r \left| \pm F_1 (\theta_2 - \theta_1) - \beta w R_\alpha \sin\alpha_1 (\alpha_2 - \alpha_1) - 2 \beta w R (\cos\alpha_2 - \cos\alpha_1) \right|$$

The Complete Solution for Bends

9. Drag for 3D wellbore section without pipe rotation for BHA

$$F_2 = F_1 e^{\pm\mu|\theta_2 - \theta_1|} + K \beta w R_\alpha (\sin\alpha_2 - \sin\alpha_1)$$

10. Torque for 3D wellbore section without axial motion for BHA

$$T = \mu r \left| \pm F_1 (\theta_2 - \theta_1) - \beta w R_\alpha \sin\alpha_1 (\alpha_2 - \alpha_1) - 2 \beta w R_\alpha (\cos\alpha_2 - \cos\alpha_1) \right|$$

11. Drag for combined motion in 3D bends for BHA

$$F_2 = F_1 + \beta w R_\alpha (\sin\alpha_2 - \sin\alpha_1) + (F_1(e^{\pm\mu|\theta_2-\theta_1|} - 1) + (K-1)\beta w R_\alpha (\sin\alpha_2 - \sin\alpha_1))\sin\psi$$

12. Torque for combined motion in 3D bends for BHA

$$T = \mu r \left| \pm F_1(\theta_2 - \theta_1) - \beta w R_\alpha \sin\alpha_1 (\alpha_2 - \alpha_1) - 2\beta w R_\alpha (\cos\alpha_2 - \cos\alpha_1) \right| \cos\psi$$

13. Weight Term

$$K = \frac{A(1-\mu^2)(\sin\alpha_2 - e^{-AB\mu(\alpha_2-\alpha_1)}\sin\alpha_1) - 2B\mu(\cos\alpha_2 - e^{-AB\mu(\alpha_2-\alpha_1)}\cos\alpha_1)}{(1+\mu^2)(\sin\alpha_2 - \sin\alpha_1)}$$

Appendix B - 3DModel Simulator manual

3D simulator was created to be as simple as possible. As a first step to accomplish torque and drag analysis is to fill in all the required data on the “Input Data” excel sheet. Drill string description must be precisely given as it is shown on the Figure 48. As OD size in the current table it is required to give tool join radius based on the analytical model description[11].

Drill String description					
№	Drill string section	Length	Weight (kg/m)	OD	Pipe density
1	Drill Pipe	2660	46.94	0.225275	7.8
2	Drill Pipe	5646	43.54	0.206225	7.8
3	Drill Pipe	1045	43.54	0.206225	7.8
4	HWDP	169.52	74.97	0.184	7.8
5	BHA	75.47097329	140.00	0.2267	7.8
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Drill Pipe
HWDP
BHA

Input Data | Calculation | ResultTable

Figure 47: Drill string description (screen shot from 3D simulator)

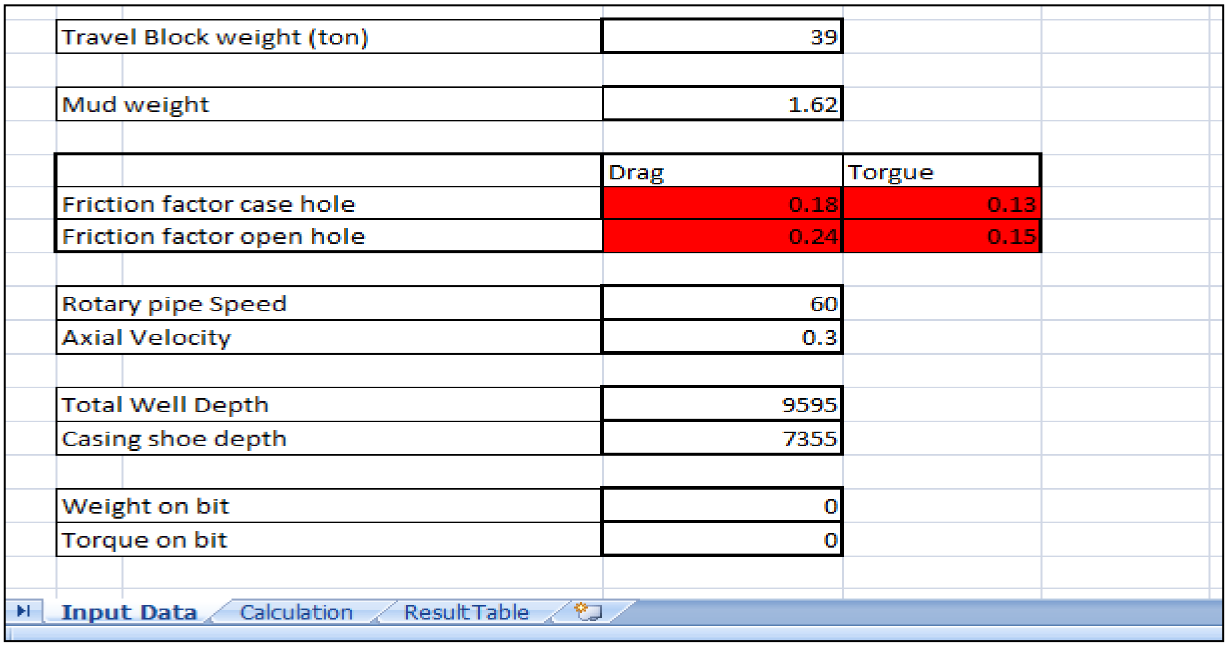
Well description						
№	Well section	Length	Inclination		Azimuth	
			α_2	α_1	φ_2	φ_1
1	Straight Vertical	460.01	0	0	274.27	274.27
2	Build-up with right side bend	659.99	0	50.93	274.27	291.78
3	Build-up with left side bend	960	50.93	80.44	291.78	272.82
4	Inclined-Tangential	1020	80.44	80.44	272.82	272.82
5	Drop-off section	160	80.44	75	272.82	274.68
6	Inclined-Tangential	520	75	75	274.68	274.68
7	Build-up section	160	75	84.02	274.68	272.64
8	Inclined-Tangential	4413.14	84.02	84.02	272.64	272.64
9	Drop-off section	408.51	84.02	61.35	272.64	267.53
10	Build-up section	321.2	61.35	90	267.53	268.02
11	Horizontal	233.88	90	90	268.02	268.02
12	Drop-off section	278.27	90	80.93	268.02	268.02
13						
14						
15						
16						
17						
18						
19						
20						

Straight Vertical
Inclined-Tangential
Build-up section
Drop-off section
Side Bend
Horizontal
Build-up with right side bend
Build-up with left side bend

Input Data | Calculation | ResultTable

Figure 48: Well section description (Screen shot from 3D simulator)

Figure 49 shows the Well section description. From the downlist, the simulator allows to select one ofthe possible wellbore section inlcuding 3-d dimentional.Where α 1, 2 and φ 1, 2 refers to two consecutive survey measurements of inclination and azimuth respectively.
The rest of the input data required for the T&D analysis are included in the Figure 50. The simulator gives a possibility to give separate friction factor values for drag and torque simulation. An application of Weight on Bit (WOB) and Torque of Bit (TOB) may also be tested, but needs to be further worked on.

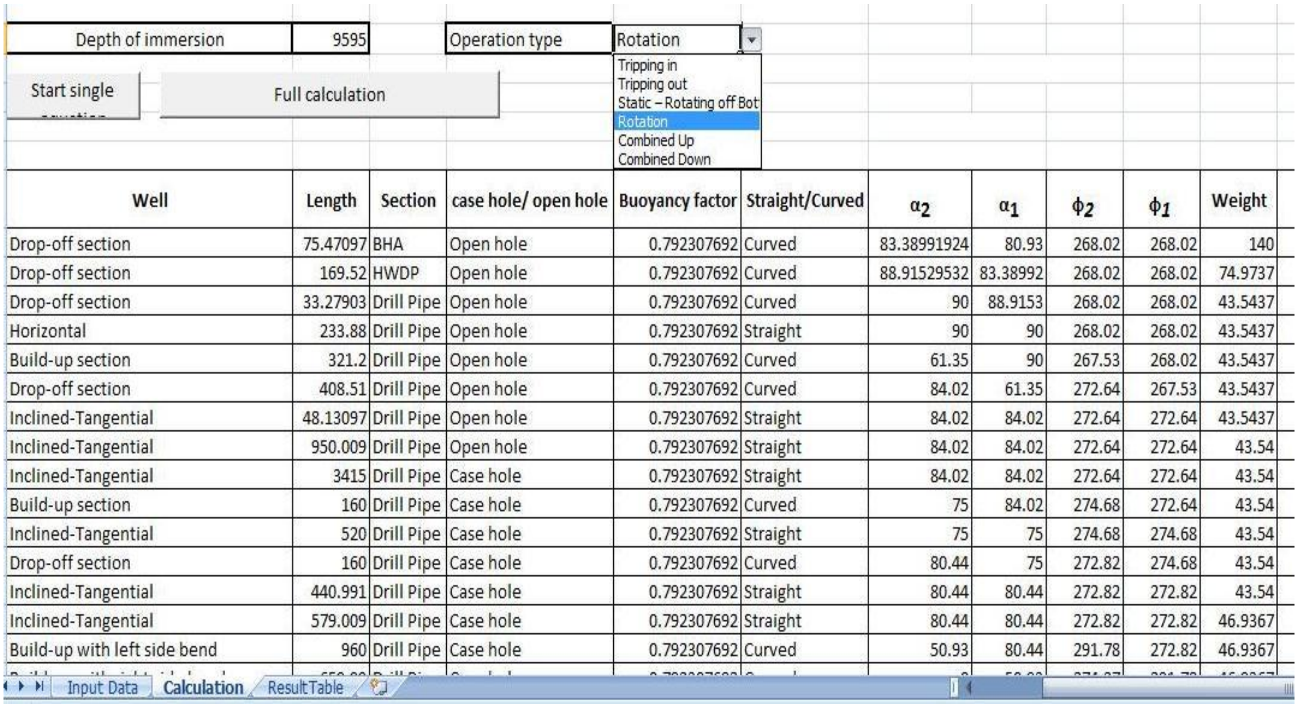


Travel Block weight (ton)	39	
Mud weight	1.62	
	Drag	Torgue
Friction factor case hole	0.18	0.13
Friction factor open hole	0.24	0.15
Rotary pipe Speed	60	
Axial Velocity	0.3	
Total Well Depth	9595	
Casing shoe depth	7355	
Weight on bit	0	
Torque on bit	0	

Input Data | Calculation | ResultTable

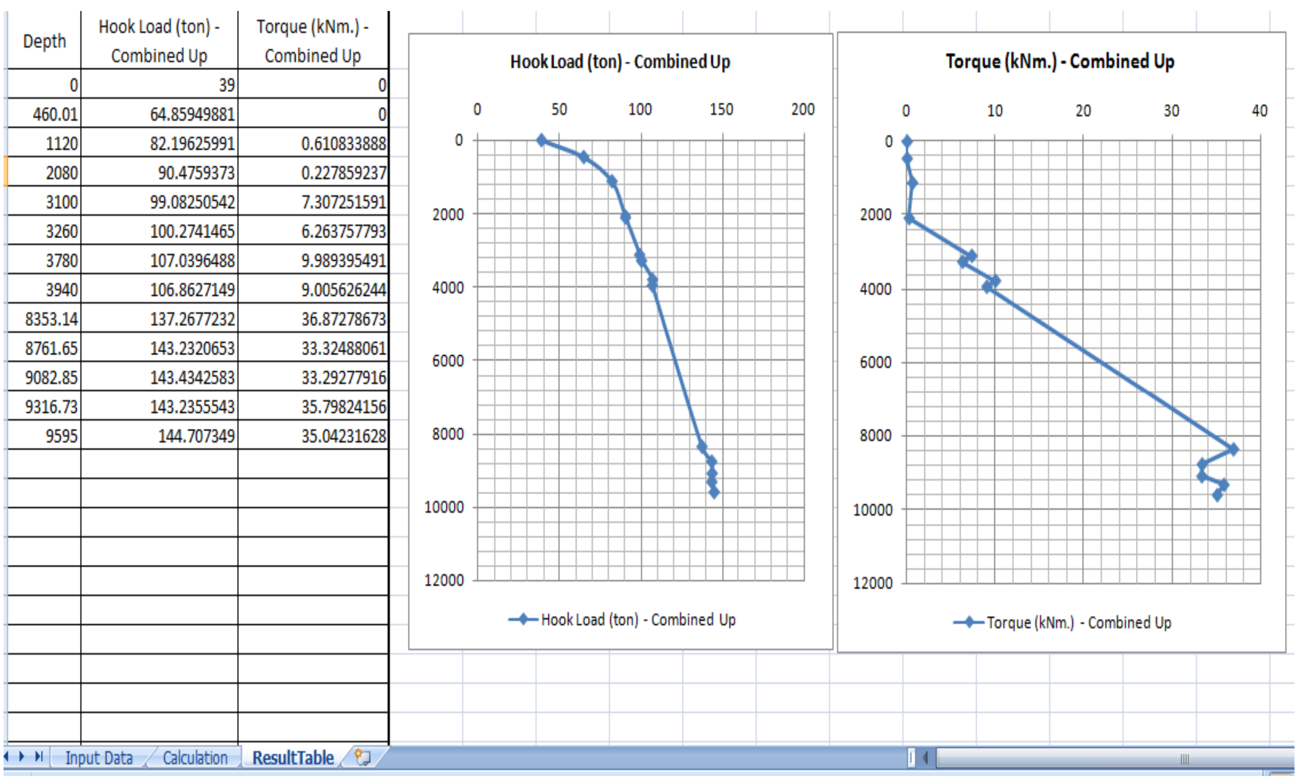
Figure 49: Input Data -3D Model simulator screen shot

As the next step, from “Calculation” sheet, it is required to select an operation that the user wants the simulation to be done as on Figure 51. The list below includes all the operations which are described in the analytical model simple solution including combined up and down motions. By pressing “Full calculation” the user will be switched to the last “Results Table”, Figure 52, where both numerical and graphical results will be shown.



Well	Length	Section	case hole/ open hole	Buoyancy factor	Straight/Curved	α_2	α_1	ϕ_2	ϕ_1	Weight
Drop-off section	75.47097	BHA	Open hole	0.792307692	Curved	83.38991924	80.93	268.02	268.02	140
Drop-off section	169.52	HWDP	Open hole	0.792307692	Curved	88.91529532	83.38992	268.02	268.02	74.9737
Drop-off section	33.27903	Drill Pipe	Open hole	0.792307692	Curved	90	88.9153	268.02	268.02	43.5437
Horizontal	233.88	Drill Pipe	Open hole	0.792307692	Straight	90	90	268.02	268.02	43.5437
Build-up section	321.2	Drill Pipe	Open hole	0.792307692	Curved	61.35	90	267.53	268.02	43.5437
Drop-off section	408.51	Drill Pipe	Open hole	0.792307692	Curved	84.02	61.35	272.64	267.53	43.5437
Inclined-Tangential	48.13097	Drill Pipe	Open hole	0.792307692	Straight	84.02	84.02	272.64	272.64	43.5437
Inclined-Tangential	950.009	Drill Pipe	Open hole	0.792307692	Straight	84.02	84.02	272.64	272.64	43.54
Inclined-Tangential	3415	Drill Pipe	Case hole	0.792307692	Straight	84.02	84.02	272.64	272.64	43.54
Build-up section	160	Drill Pipe	Case hole	0.792307692	Curved	75	84.02	274.68	272.64	43.54
Inclined-Tangential	520	Drill Pipe	Case hole	0.792307692	Straight	75	75	274.68	274.68	43.54
Drop-off section	160	Drill Pipe	Case hole	0.792307692	Curved	80.44	75	272.82	274.68	43.54
Inclined-Tangential	440.991	Drill Pipe	Case hole	0.792307692	Straight	80.44	80.44	272.82	272.82	43.54
Inclined-Tangential	579.009	Drill Pipe	Case hole	0.792307692	Straight	80.44	80.44	272.82	272.82	46.9367
Build-up with left side bend	960	Drill Pipe	Case hole	0.792307692	Curved	50.93	80.44	291.78	272.82	46.9367

Figure 50: Calculation sheet -3D Model simulator screen shot



Depth	Hook Load (ton) - Combined Up	Torque (kNm.) - Combined Up
0	39	0
460.01	64.85949881	0
1120	82.19625991	0.610833888
2080	90.4759373	0.227859237
3100	99.08250542	7.307251591
3260	100.2741465	6.263757793
3780	107.0396488	9.989395491
3940	106.8627149	9.005626244
8353.14	137.2677232	36.87278673
8761.65	143.2320653	33.32488061
9082.85	143.4342583	33.29277916
9316.73	143.2355543	35.79824156
9595	144.707349	35.04231628

Figure 51: Result Table -3D Model simulator screen shot

Appendix C - Test Wells

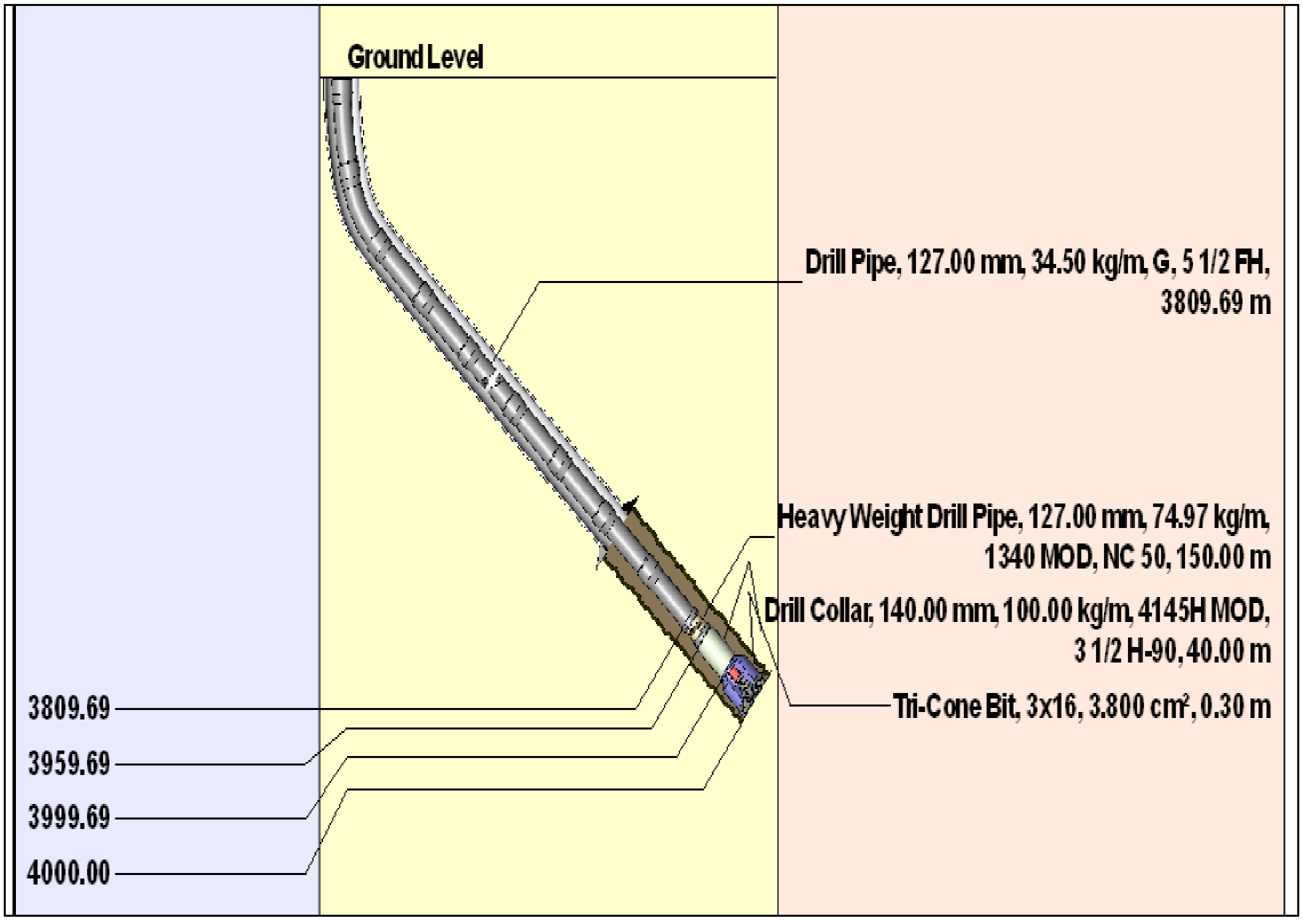


Figure 52: Test Well 1 Schematic

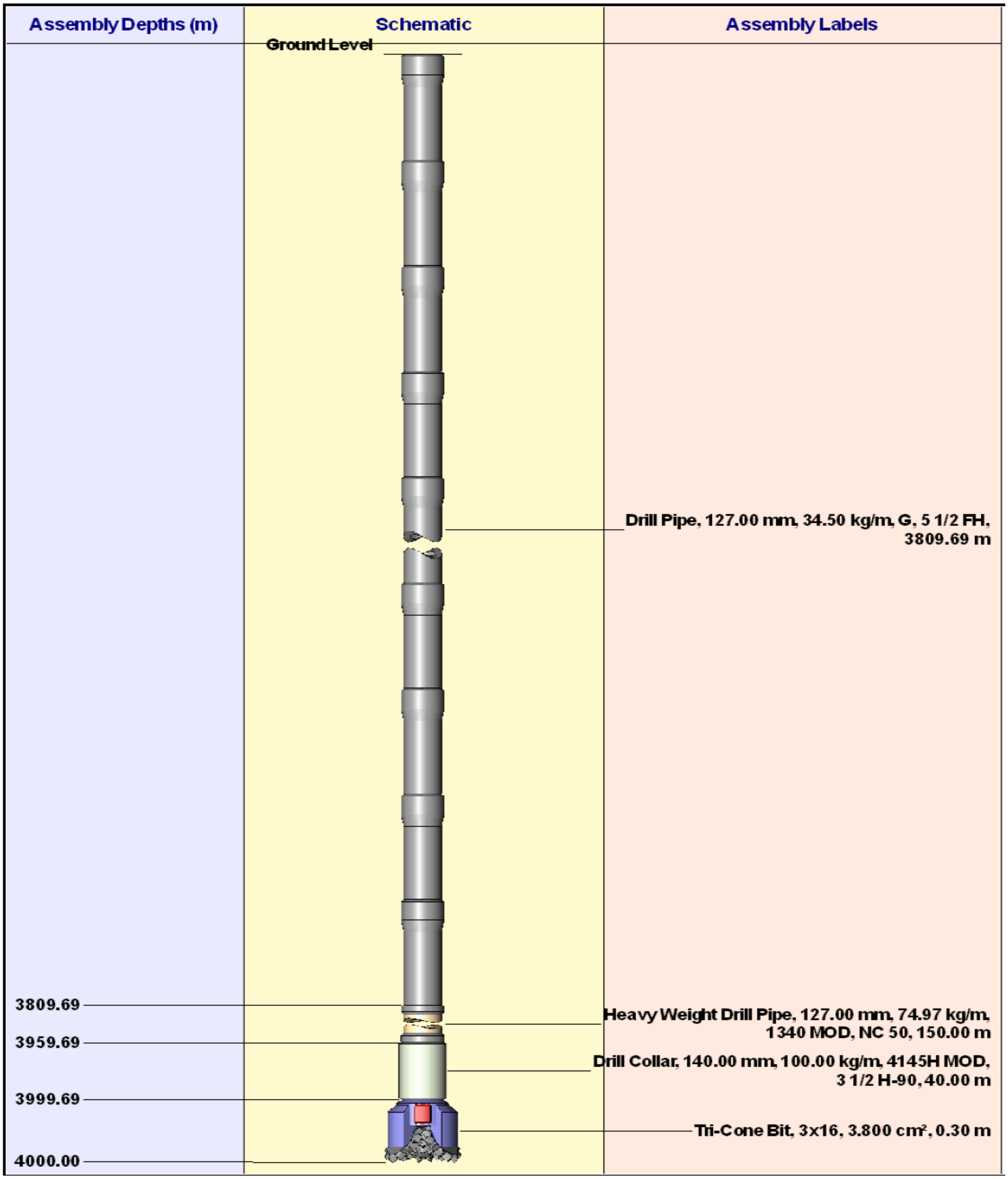


Figure 53: The simplified drillstring for Test well 1

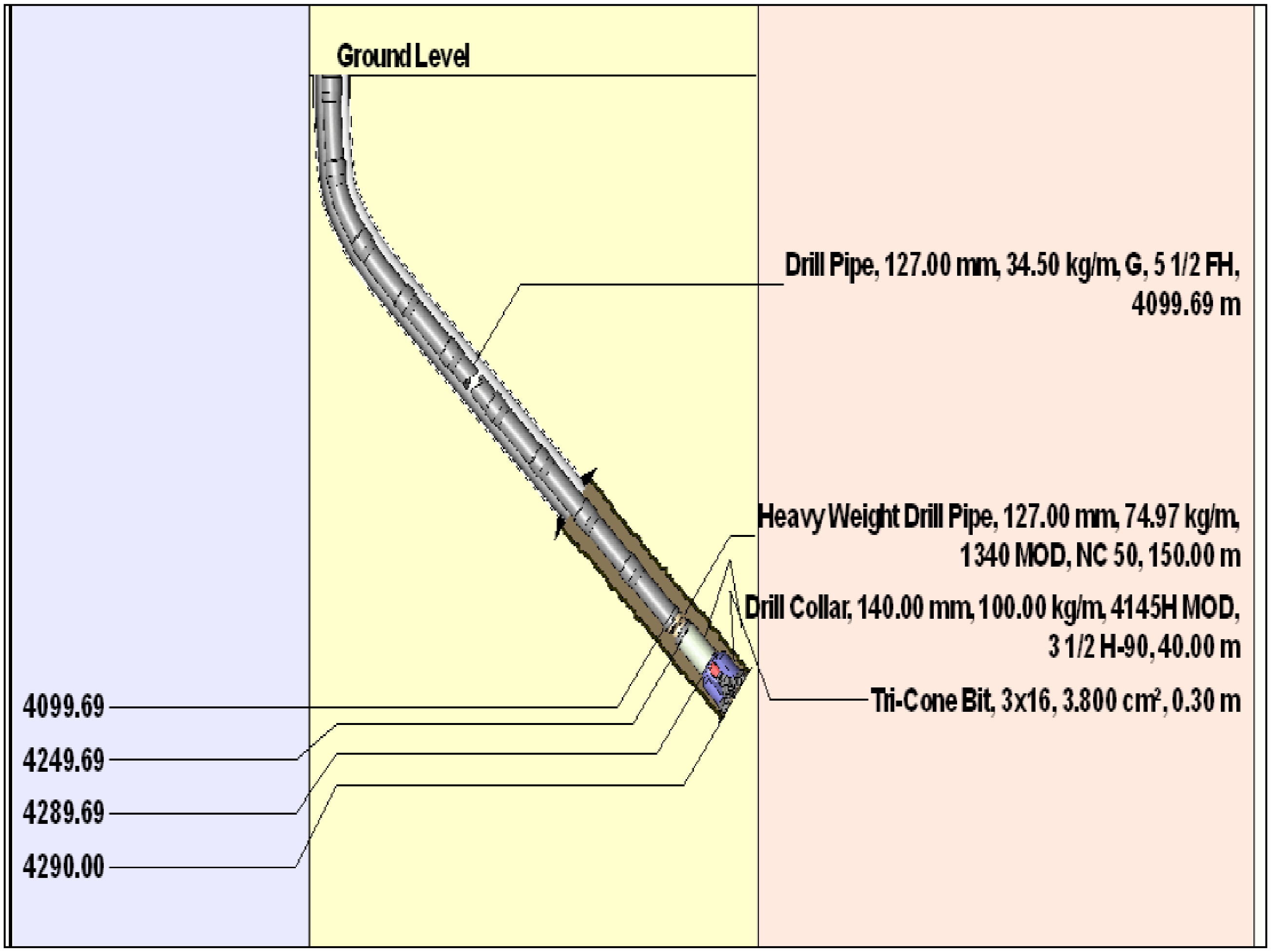


Figure 54: Test Well 2 Schematic

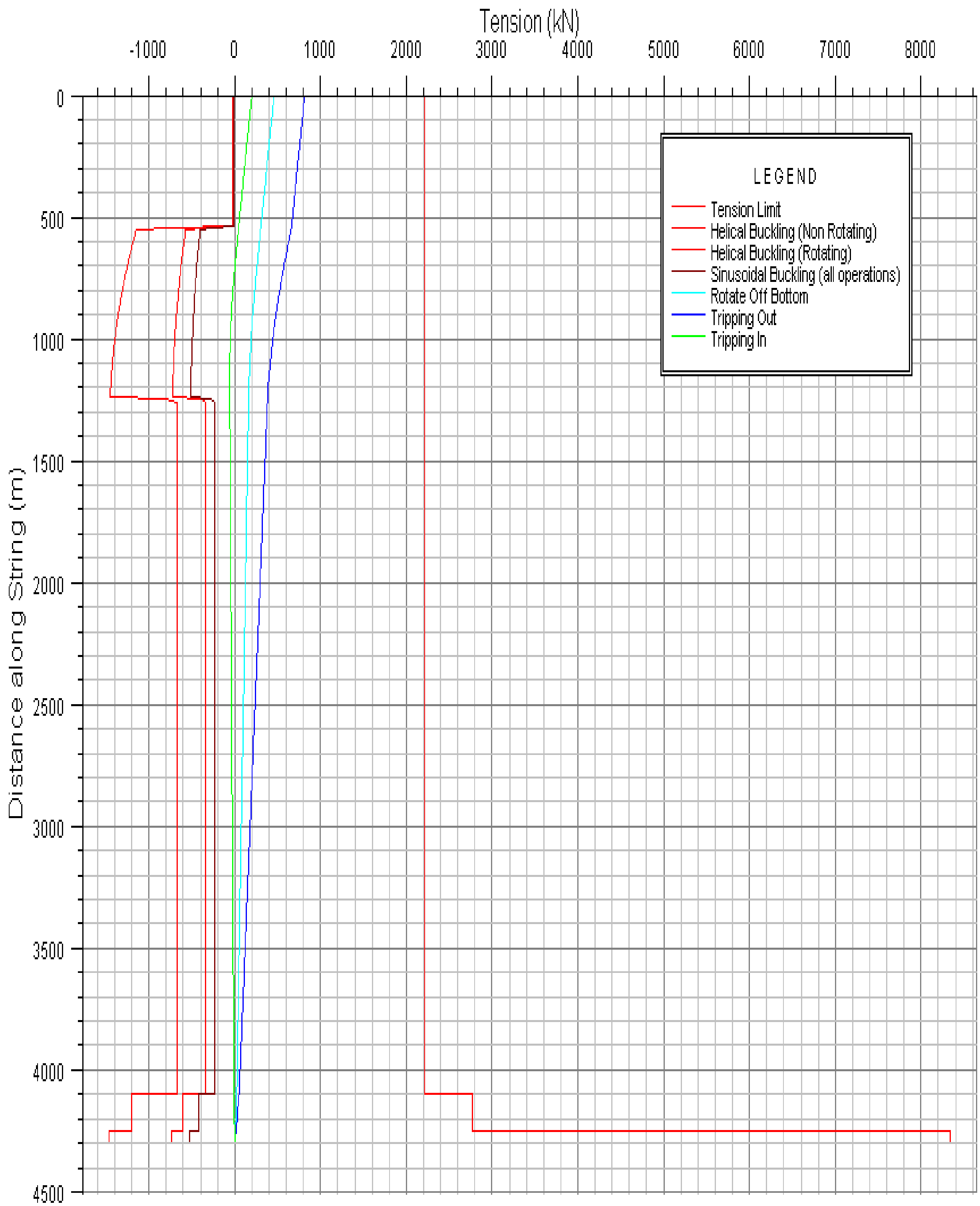


Figure 55: Effective Tension Test Well 4

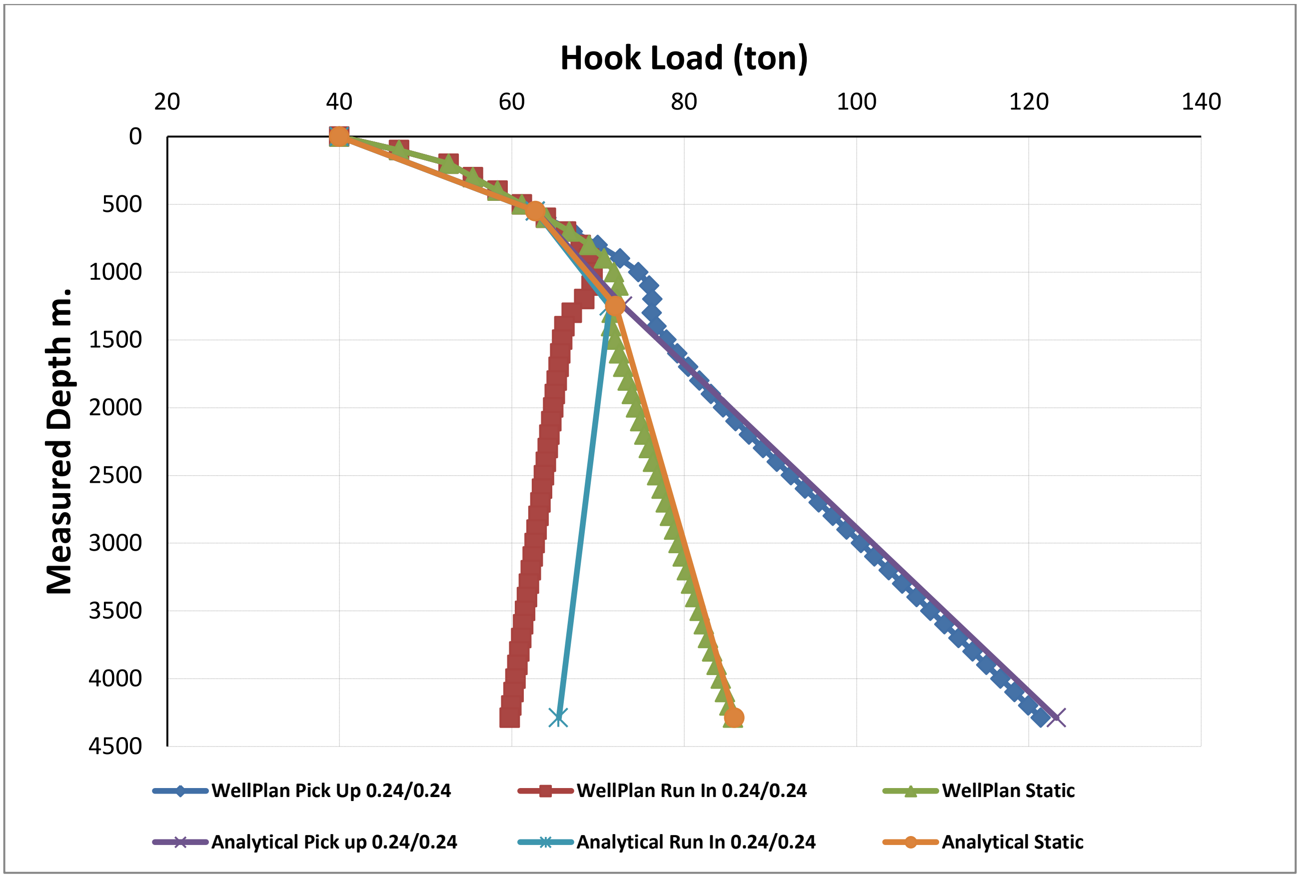


Figure 56: Comparison between hook load weight, the analytical model vsWellplan simulation-Test Well 4

Table 16: Test well 5 3d-dimentional well section survey

Well section	Length	Inclination		Azimuth	
		α_2	α_1	φ_2	φ_1
Straight Vertical	550	0	0	100	100
Build-up section	700	0	80	100	135
Inclined-Tangential	3040	80	80	135	135

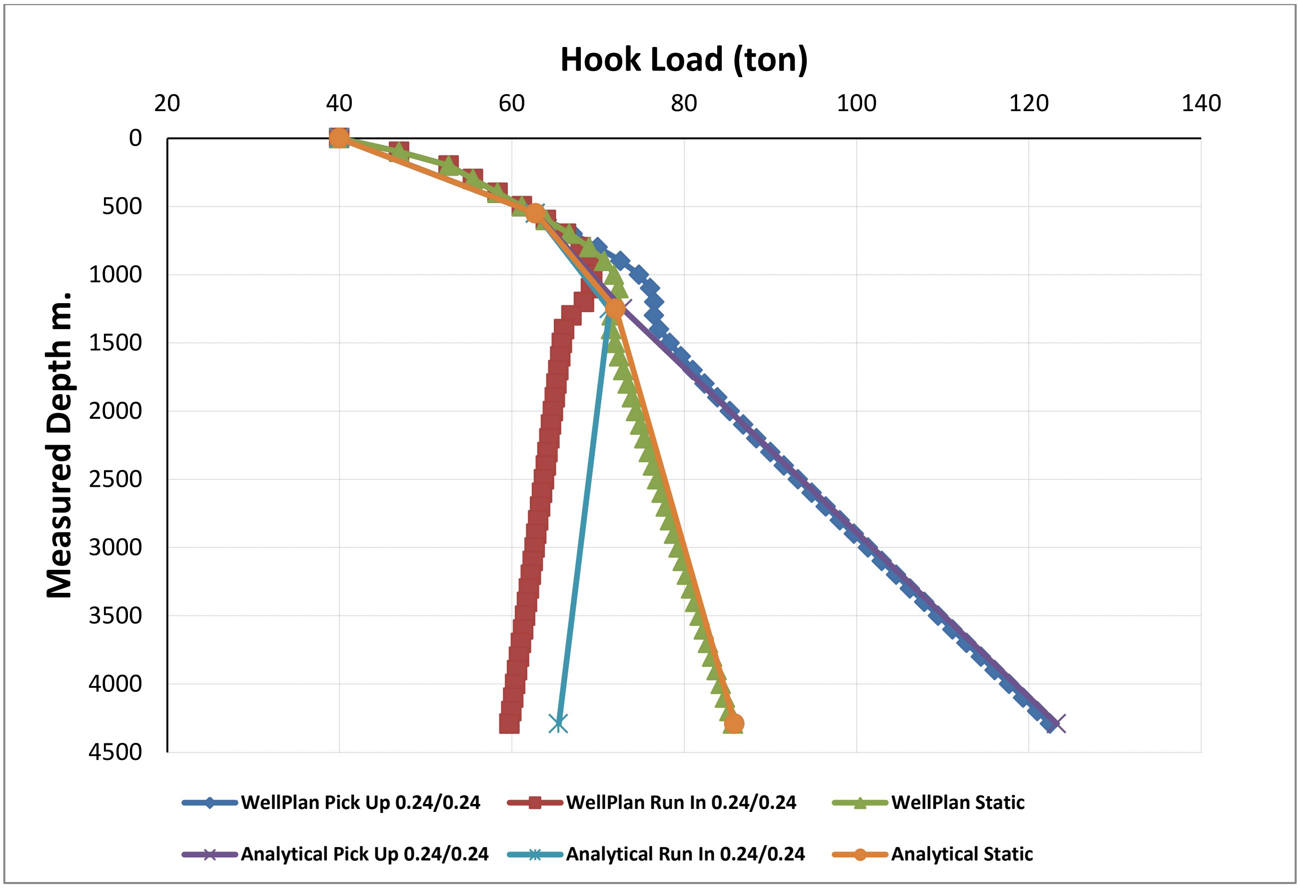


Figure 57: Comparison between hook load weight, the analytical model vs Wellplan simulation-Test Well4

Appendix D - Real Well 1

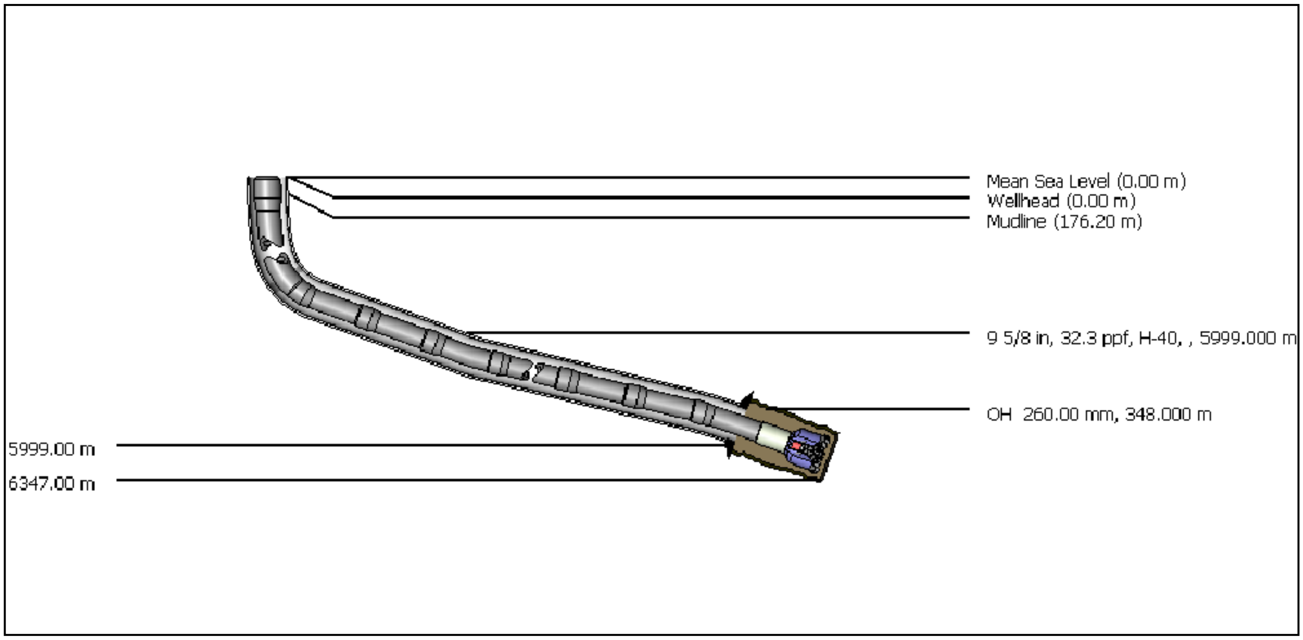


Figure 58: Well Schematic-Full String – Well 1

Table 17: Drillstring and BHA Details - Real Well 1

Type	Length	Depth	Body		Stabilizer / Tool Joint				Weight	Material	Grade	Class
			OD	ID	Avg. Joint Length	Length	OD	ID				
	(m)	(m)	(mm)	(mm)	(m)	(m)	(mm)	(mm)	(kg/m)			
Drill Pipe	1 191.086	1 191.09	149.26	121.36	9.14	0.457	177.80	101.60	39.78	CS_API 5D/7	E	1
Drill Pipe	5 000.000	6 191.09	127.00	108.61	9.14	0.433	177.80	95.25	34.18	CS_API 5D/7	E	1
Heavy Weight Drill Pipe	9.400	6 200.49	127.00	76.20	9.14	1.219	165.10	77.80	76.15	CS_1340 MOD	1340 MOD	
Accelerator	3.938	6 204.42	177.80	63.50					170.25	CS_API 5D/7	4145H MOD	
Heavy Weight Drill Pipe	80.000	6 284.42	127.00	76.20	9.14	1.219	165.10	77.80	76.15	CS_1340 MOD	1340 MOD	
Mechanical Jar	3.200	6 287.62	177.80	63.50					122.00	SS_15-15LC	15-15LC MOD (1)	
Heavy Weight Drill Pipe	10.000	6 297.62	127.00	76.20	9.14	1.219	165.10	77.80	76.15	CS_1340 MOD	1340 MOD	
Cross Over	1.100	6 298.72	188.98	60.96					199.12	CS_API 5D/7	4145H MOD	
Adjustable Stabilizer	2.972	6 301.70	165.10	44.45		0.536	184.15		211.00	CS_API 5D/7	4145H MOD	
Drill Collar	9.410	6 311.11	171.45	38.10					149.00	CS_API 5D/7	4145H MOD	
Adjustable Stabilizer	7.000	6 318.11	177.80	44.45		0.536	184.15		166.88	CS_API 5D/7	4145H MOD	
Adjustable Stabilizer	2.972	6 321.08	165.10	44.45		0.536	184.15		153.00	CS_API 5D/7	4145H MOD	
MWD Tool	11.500	6 332.58	171.45	101.60					166.88	SS_15-15LC	15-15LC MOD (1)	
Adjustable Stabilizer	2.972	6 335.55	165.10	44.45		0.536	184.15		166.00	CS_API 5D/7	4145H MOD	
Drill Collar	2.800	6 338.35	165.10	31.75					162.41	CS_API 5D/7	4145H MOD	
Bent Housing	8.345	6 346.70	177.80	63.50					138.76	CS_API 5D/7	4145H MOD	
Tri-Cone Bit	0.305	6 347.00	215.90						238.40			

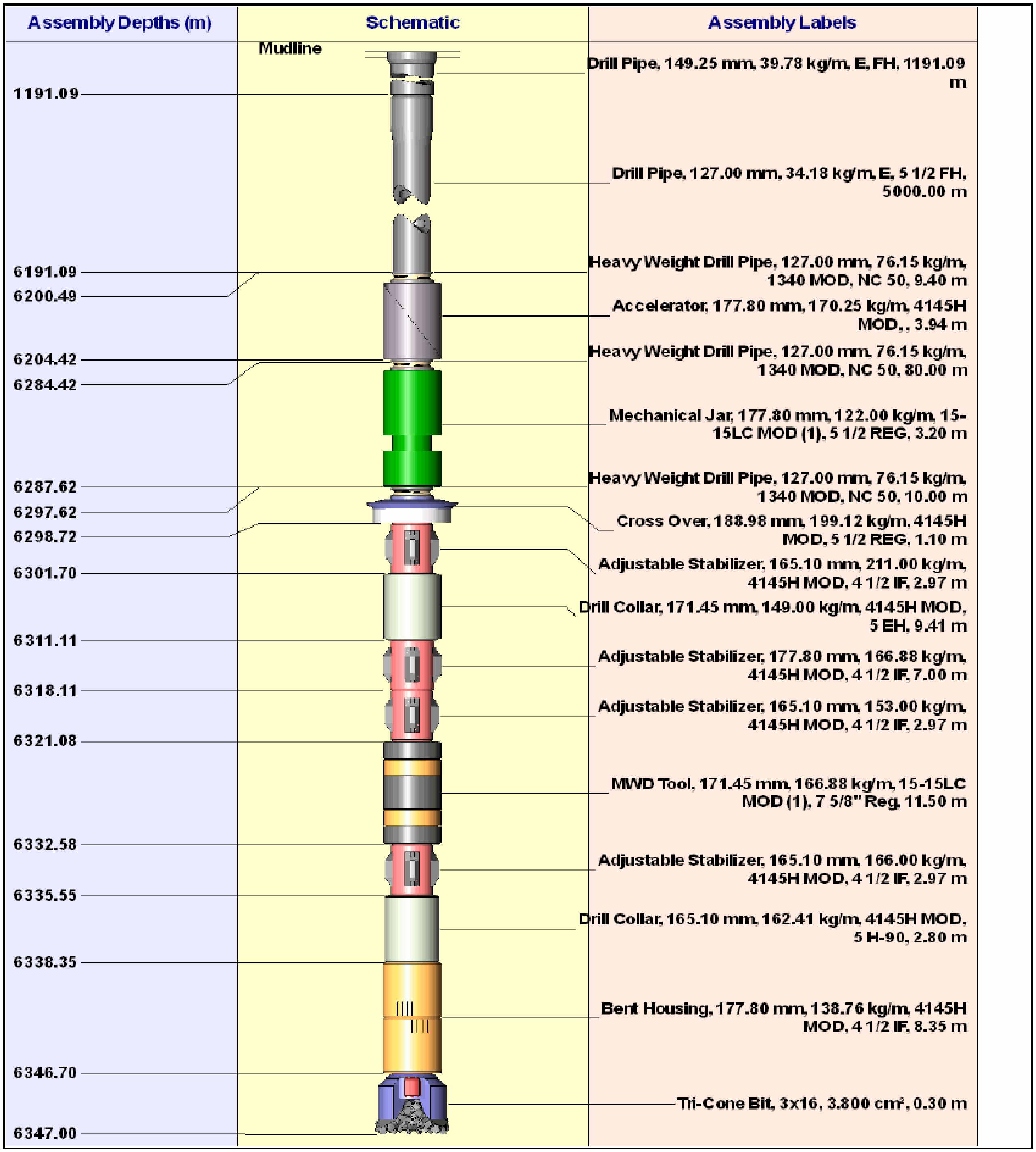


Figure 59: Drillstring and BHA Details –Real Well 1

Table 18: Drilling Fluid Details – Real Well 1

Hole Size (in)	Mud Type	Drilled Interval (m)	Mud Weight (sg)	PV (cp)	YP (lb/100ft2)	Yield Stress (lb/100ft2)	HPHT (ml/30 min)	ES (volts)	CaCl (%)	Losses* (bbls)
8 ½" x 10 ¼"	ENVIROMUL	6003-6347	1.38	29-38	25-32	10-12	1.2-1.6	405-525	21-24	173

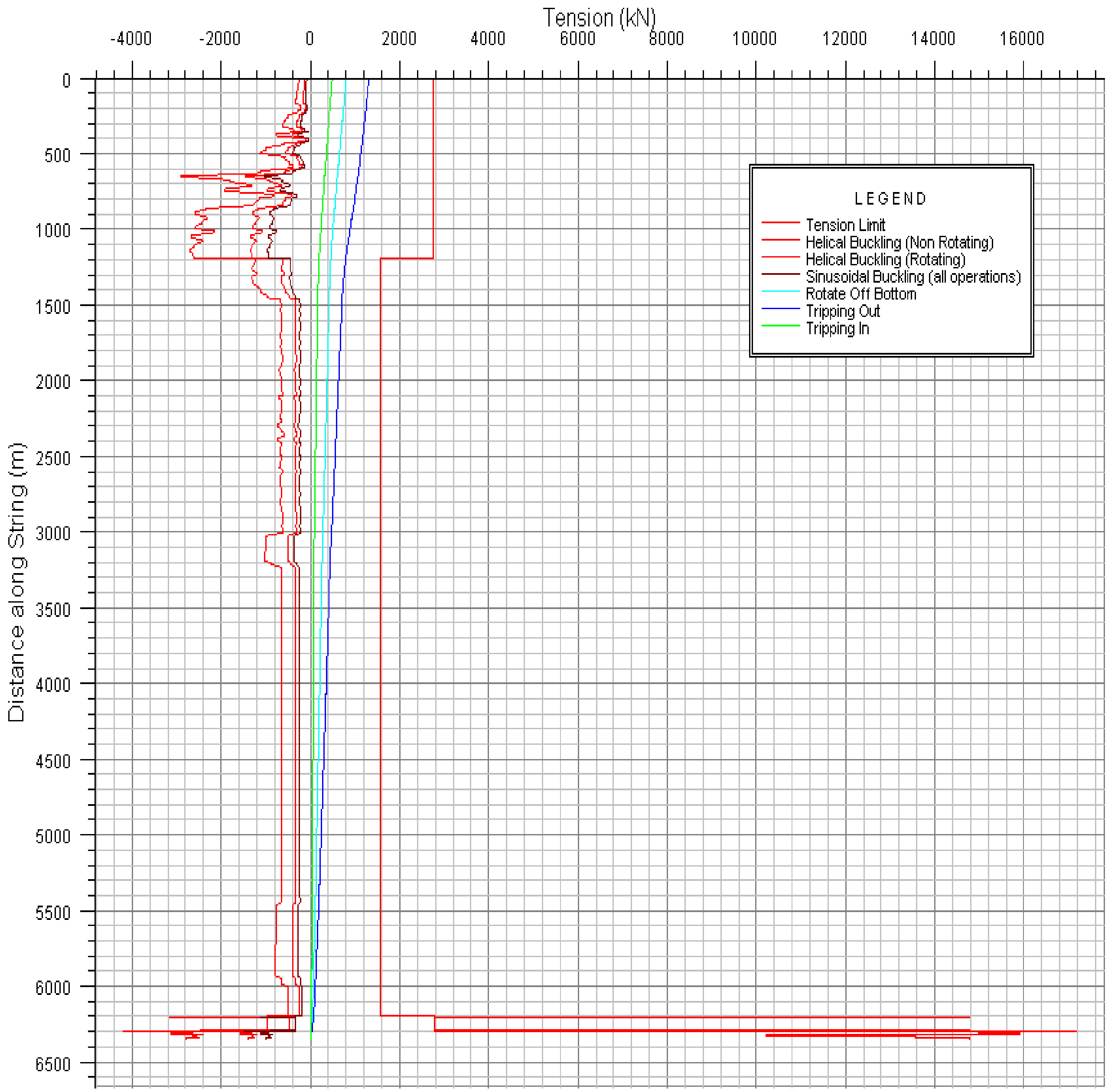


Figure 60: Effective Tension -Real Well 1

Appendix E - Oseberg-F-9

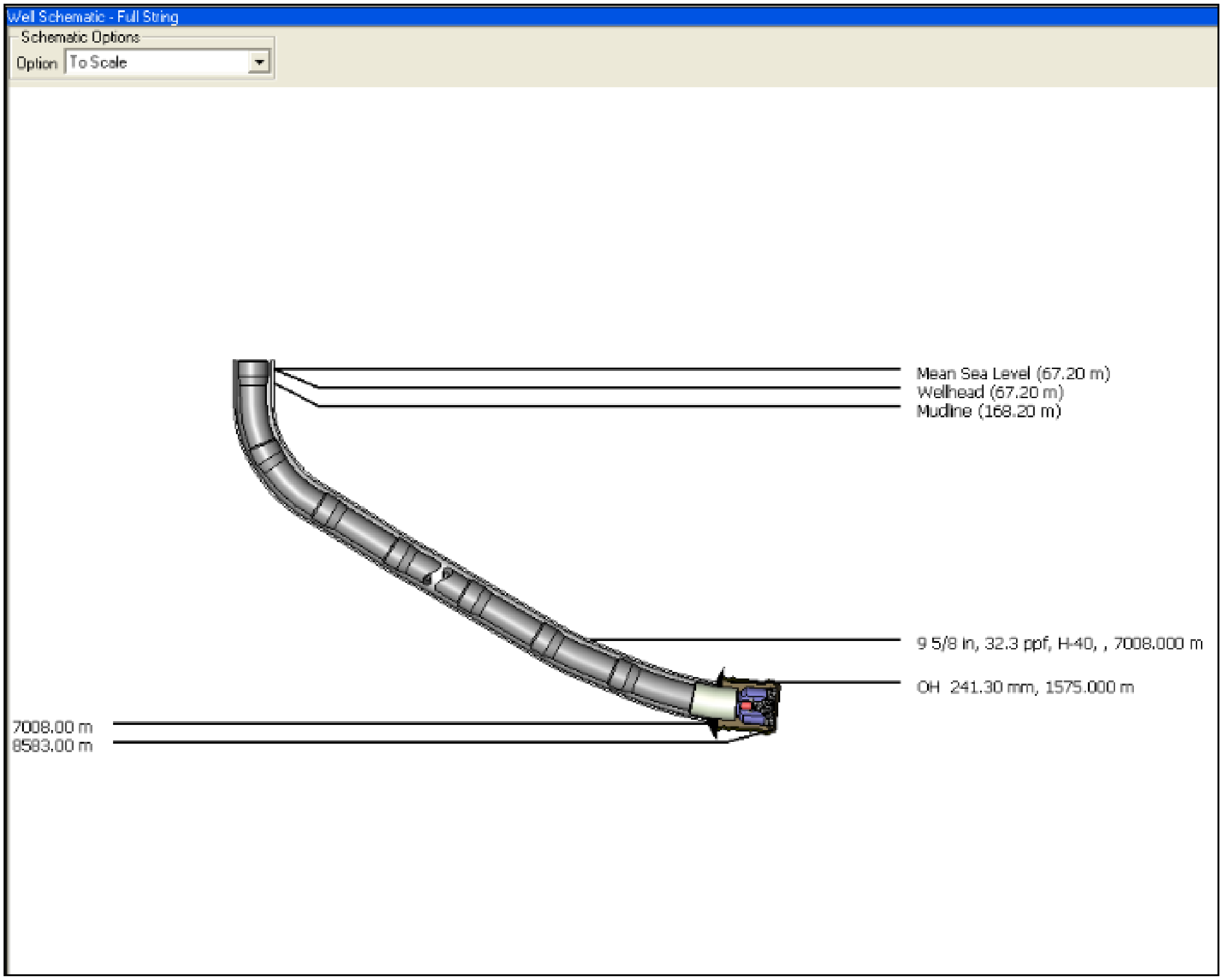


Figure 61: Well Schematic-Oseberg-F9

Table 19: Drillstring and BHA Details -Oseberg-F9

Type	Length	Depth	Body		Stabilizer / Tool Joint				Weight	Material	Grade	Class
			OD	ID	Avg. Joint Length	Length	OD	ID				
	(m)	(m)	(mm)	(mm)	(m)	(m)	(mm)	(mm)	(kg/m)			
Drill Pipe	4 374.726	4 374.73	168.28	151.51	9.14	0.482	203.20	127.00	43.25	CS_API 5D/7	E	1
Cross Over	1.070	4 375.80	184.15	60.96					142.57	CS_API 5D/7	4145H MOD	
Drill Pipe	2 340.990	6 716.79	149.22	128.14	9.14		177.80	107.95	39.70	CS_API 5D/7	G	1
Cross Over	1.090	6 717.88	168.28	60.96					106.54	CS_API 5D/7	4145H MOD	
Drill Pipe	1 650.830	8 368.71	127.00	101.60	9.14	0.433	159.54	69.85	34.14	CS_API 5D/7	G	P
Heavy Weight Drill Pipe	27.300	8 396.01	127.00	76.20	9.14	1.219	165.10	77.80	73.96	CS_1340 MOD	1340 MOD	
Accelerator	11.280	8 407.29	168.28	57.15					135.24	CS_API 5D/7	4145H MOD	
Heavy Weight Drill Pipe	81.800	8 489.09	127.00	76.20	9.14	1.219	165.10	77.80	73.96	CS_1340 MOD	1340 MOD	
Mechanical Jar	9.240	8 498.33	171.45	63.50					103.27	SS_15-15LC	15-15LC MOD (1)	
Heavy Weight Drill Pipe	27.340	8 525.67	127.00	76.20	9.14	1.219	165.10	77.80	73.96	CS_1340 MOD	1340 MOD	
Adjustable Stabilizer	2.972	8 528.64	171.45	44.45		0.536	200.03		132.79	CS_API 5D/7	4145H MOD	
Logging While Drilling	9.400	8 538.04	172.97	48.77					150.00	SS_15-15LC	15-15LC MOD (1)	
Float Sub	0.930	8 538.97	171.75	60.96					106.54	CS_API 5D/7	4145H MOD	
Underreamer	4.140	8 543.11	215.00	25.40					77.24	CS_API 5CT	V-150	
Cross Over	2.310	8 545.42	171.75	60.96					156.36	CS_API 5D/7	4145H MOD	
Adjustable Stabilizer	2.972	8 548.39	171.45	44.45		0.536	203.20		137.36	CS_API 5D/7	4145H MOD	
MWD Tool	5.660	8 554.05	174.62	73.03					142.82	SS_15-15LC	15-15LC MOD (1)	
Logging While Drilling	3.600	8 557.65	169.93	48.77					150.00	SS_15-15LC	15-15LC MOD (1)	
Logging While Drilling	5.640	8 563.29	209.55	48.77					142.82	SS_15-15LC	15-15LC MOD (1)	
Logging While Drilling	9.450	8 572.74	212.73	48.77					138.55	SS_15-15LC	15-15LC MOD (1)	
Logging While Drilling	2.800	8 575.54	171.45	48.77					142.82	SS_15-15LC	15-15LC MOD (1)	
Cross Over	7.080	8 582.62	212.73	60.96					142.82	CS_API 5D/7	4145H MOD	
Tri-Cone Bit	0.380	8 583.00	215.90						133.93			

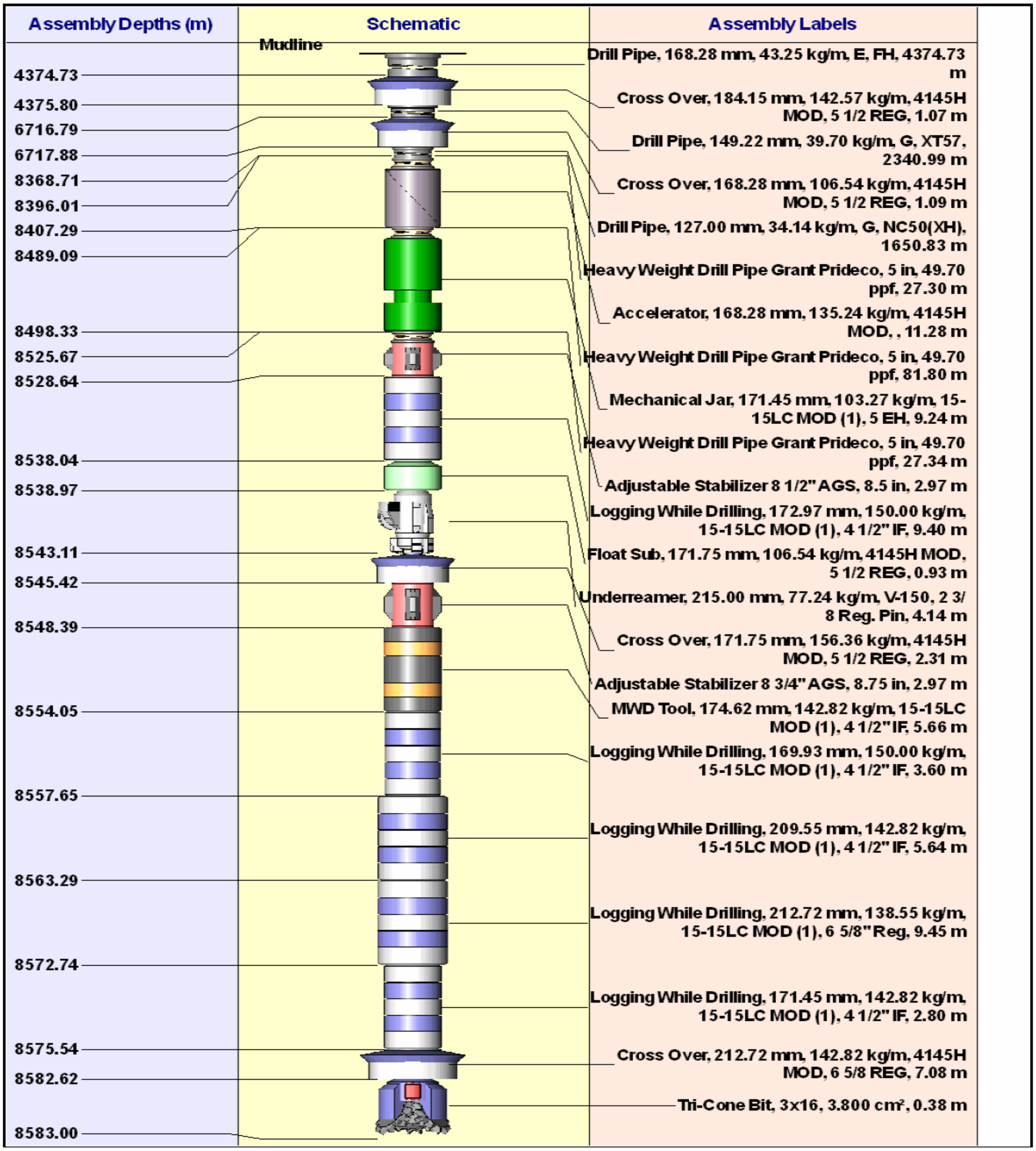


Figure 62: Drillstring and BHA Details -Oseberg-F9

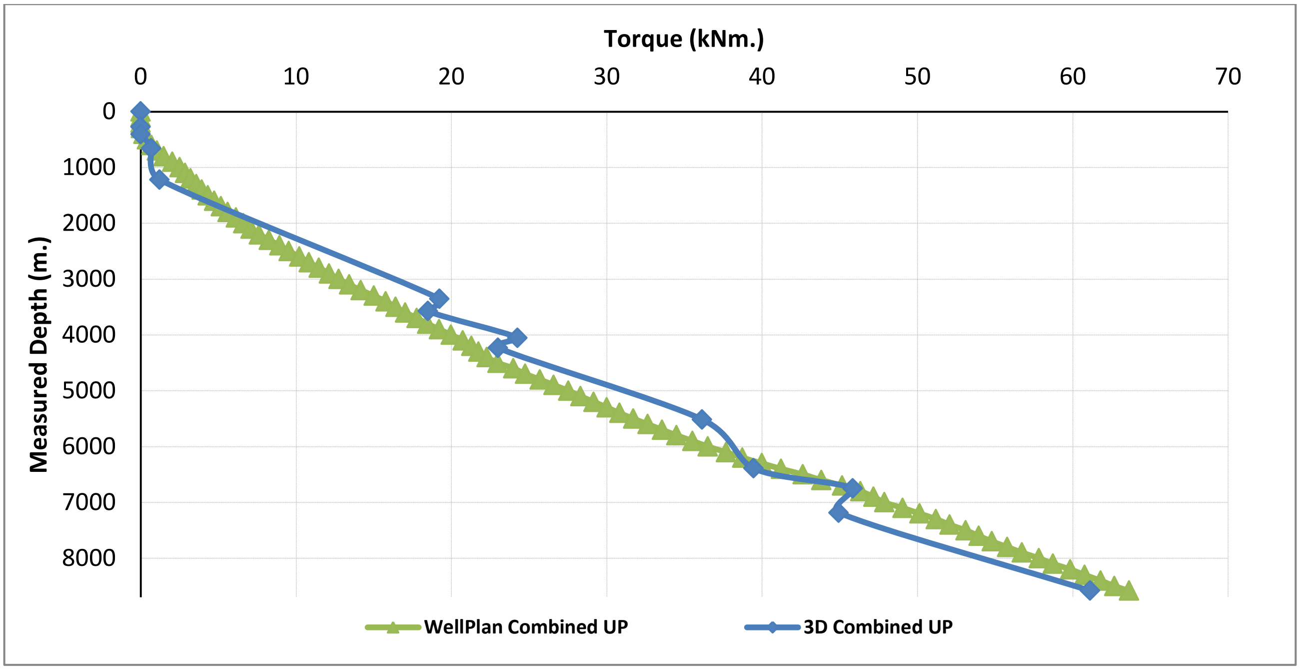


Figure 63: Comparison between torque off bottom values simulated with 3D Model and Wellplan –Combined Up motion

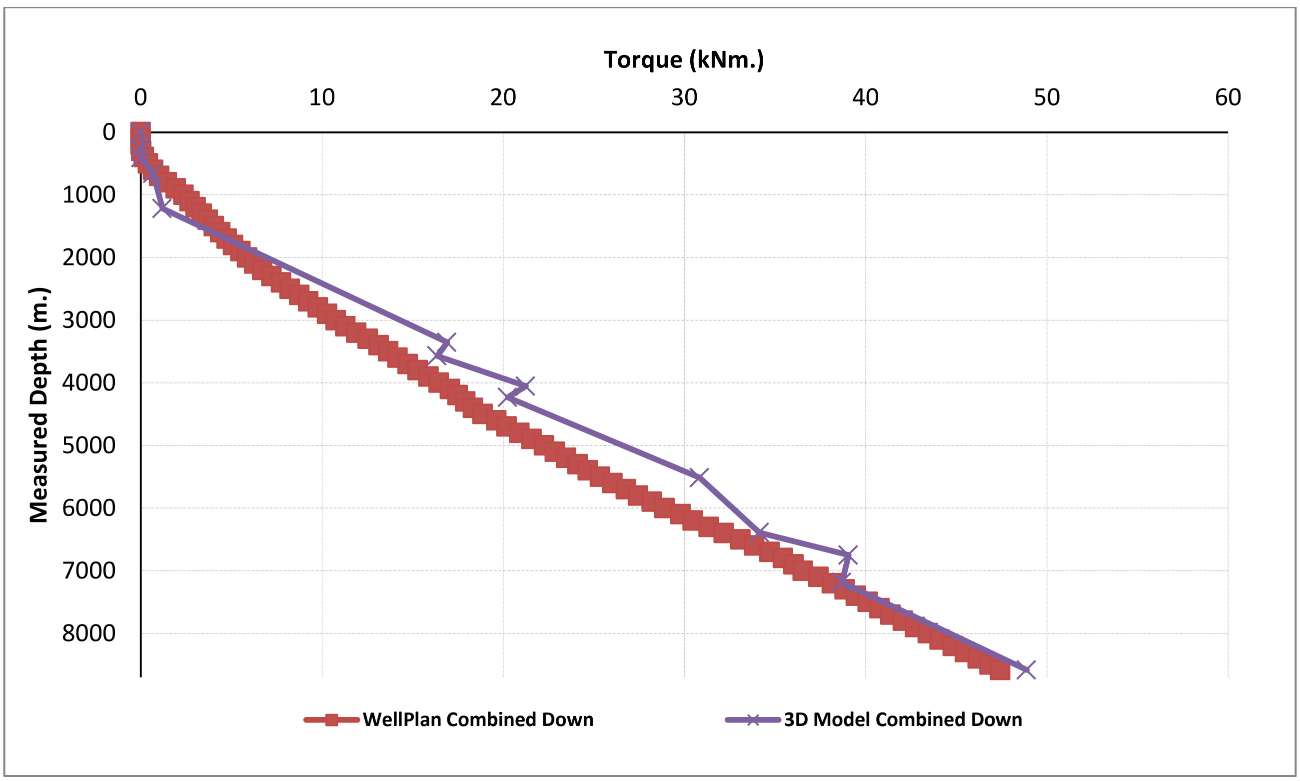


Figure 64: Comparison between torque off bottom values simulated with 3D Model and Wellplan –Combined Down motion

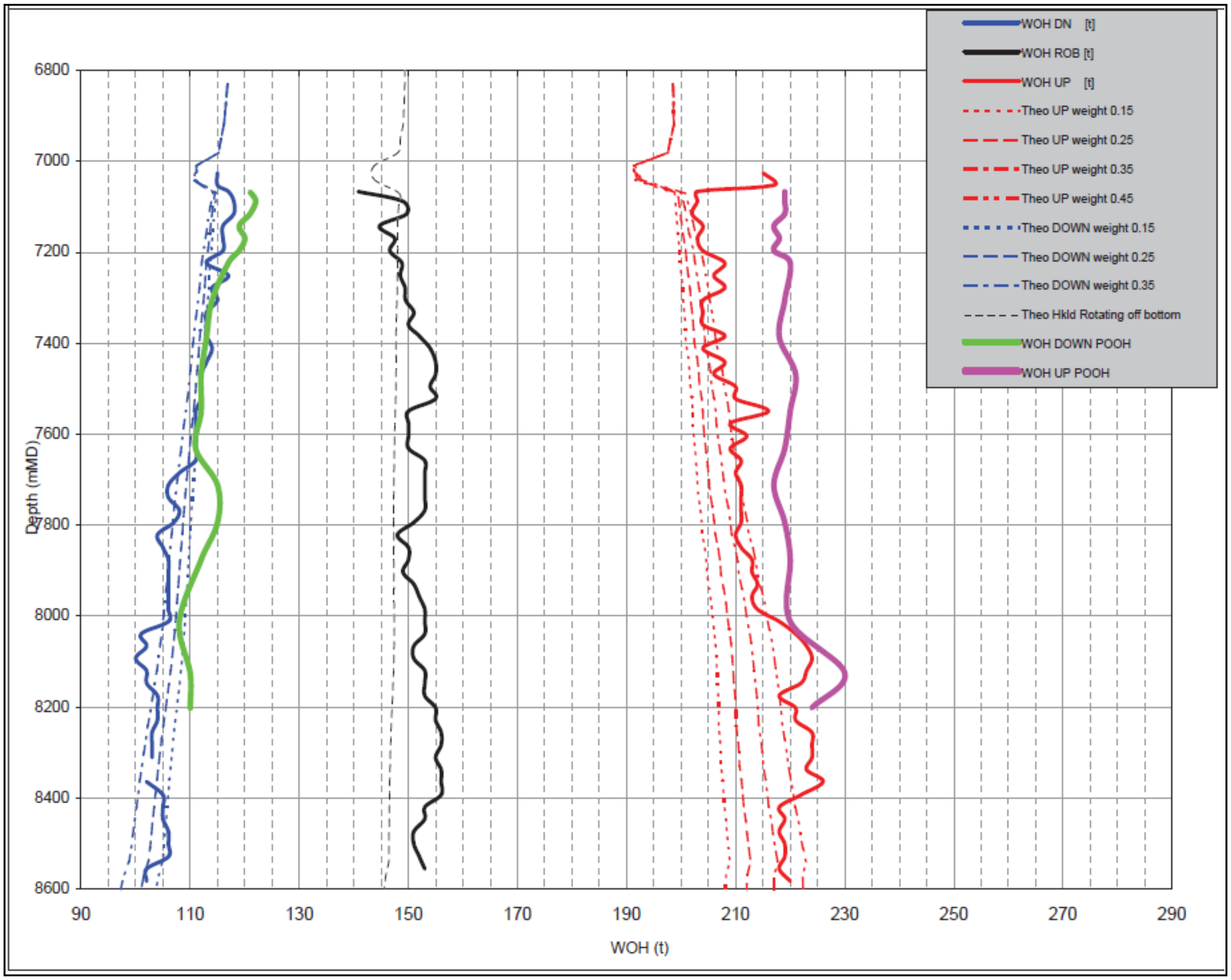


Figure 65: Tripping drag comparison for F9 well

Appendix F - Real Well 2

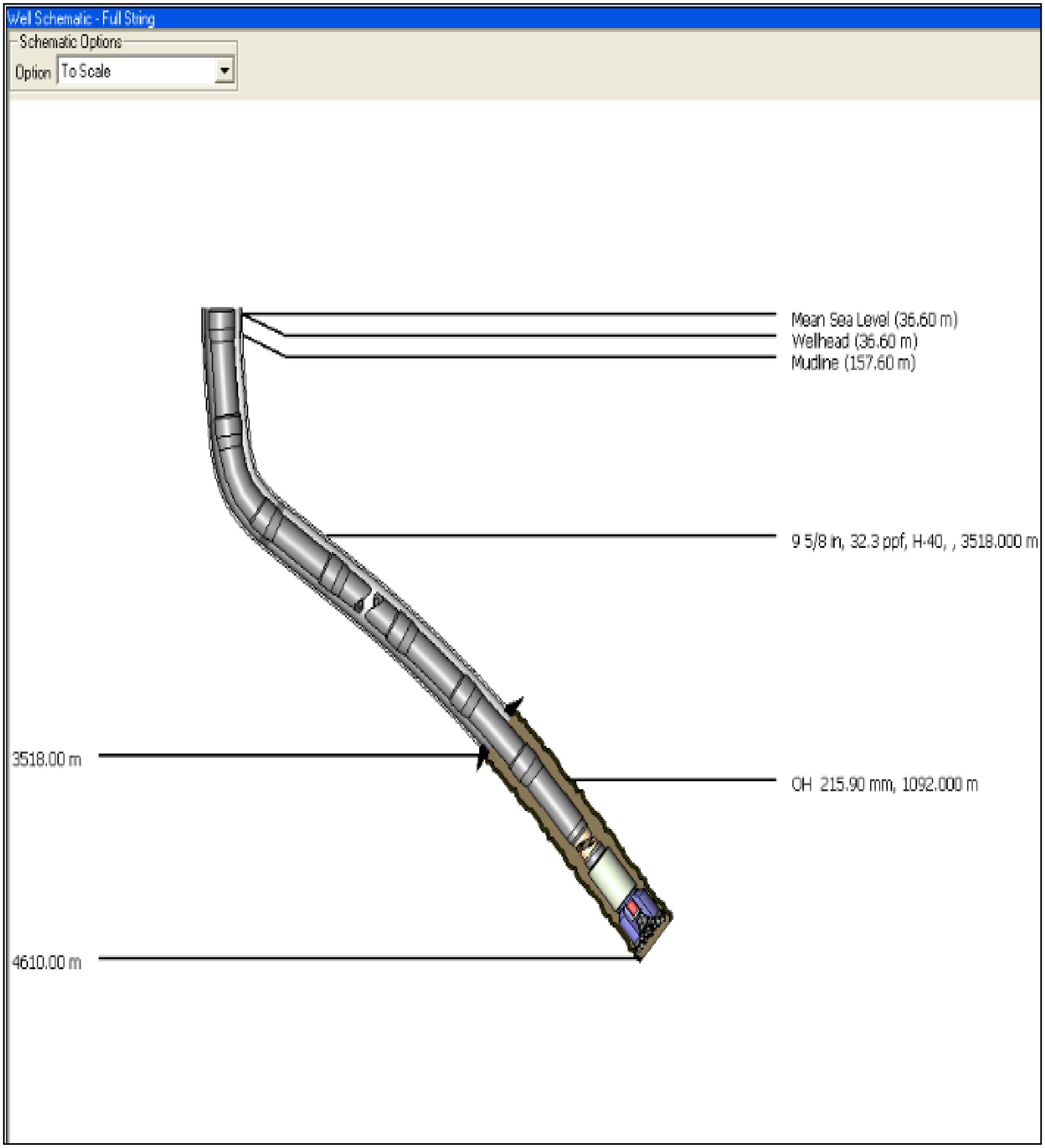


Figure 66: Well Schematic-Real Well 2

Table 20: Drillstring and BHA Details -Real Well 2

Type	Length	Depth	Body		Stabilizer / Tool Joint				Weight	Material	Grade	Class
			OD	ID	Avg. Joint Length	Length	OD	ID				
	(m)	(m)	(mm)	(mm)	(m)	(m)	(mm)	(mm)	(kg/m)			
Drill Pipe	4 034.110	4 034.11	149.23	118.62	9.14	0.457	172.24	88.90	43.54	CS_API 5D/7	G	P
Cross Over	1.840	4 035.95	176.78	60.96					170.04	CS_API 5D/7	4145H MOD	
Drill Pipe	338.770	4 374.72	88.90	70.21	9.14	0.469	113.51	65.09	20.94	CS_API 5D/7	G	P
Heavy Weight Drill Pipe	169.220	4 543.94	88.90	57.15	9.14	1.219	120.65	58.75	34.53	CS_1340 MOD	1340 MOD	
Mechanical Jar	3.300	4 547.24	120.65	50.80					69.20	SS_15-15LC	15-15LC MOD (1)	
Drill Collar	55.040	4 602.28	120.65	57.15					69.60	CS_API 5D/7	4145H MOD	
Mechanical Jar	3.400	4 605.68	120.65	50.80					69.20	SS_15-15LC	15-15LC MOD (1)	
Mechanical Jar	1.020	4 606.70	120.65	50.80					69.20	SS_15-15LC	15-15LC MOD (1)	
Bit Sub	0.590	4 607.29	123.83	54.86					60.40	CS_API 5D/7	4145H MOD	
Junk Basket	0.680	4 607.97	147.00	48.77					104.41	CS_API 5D/7	4145H MOD	
Junk Basket	1.160	4 609.13	127.00	48.77					104.41	CS_API 5D/7	4145H MOD	
Tri-Cone Bit	0.870	4 610.00	152.40						52.09			

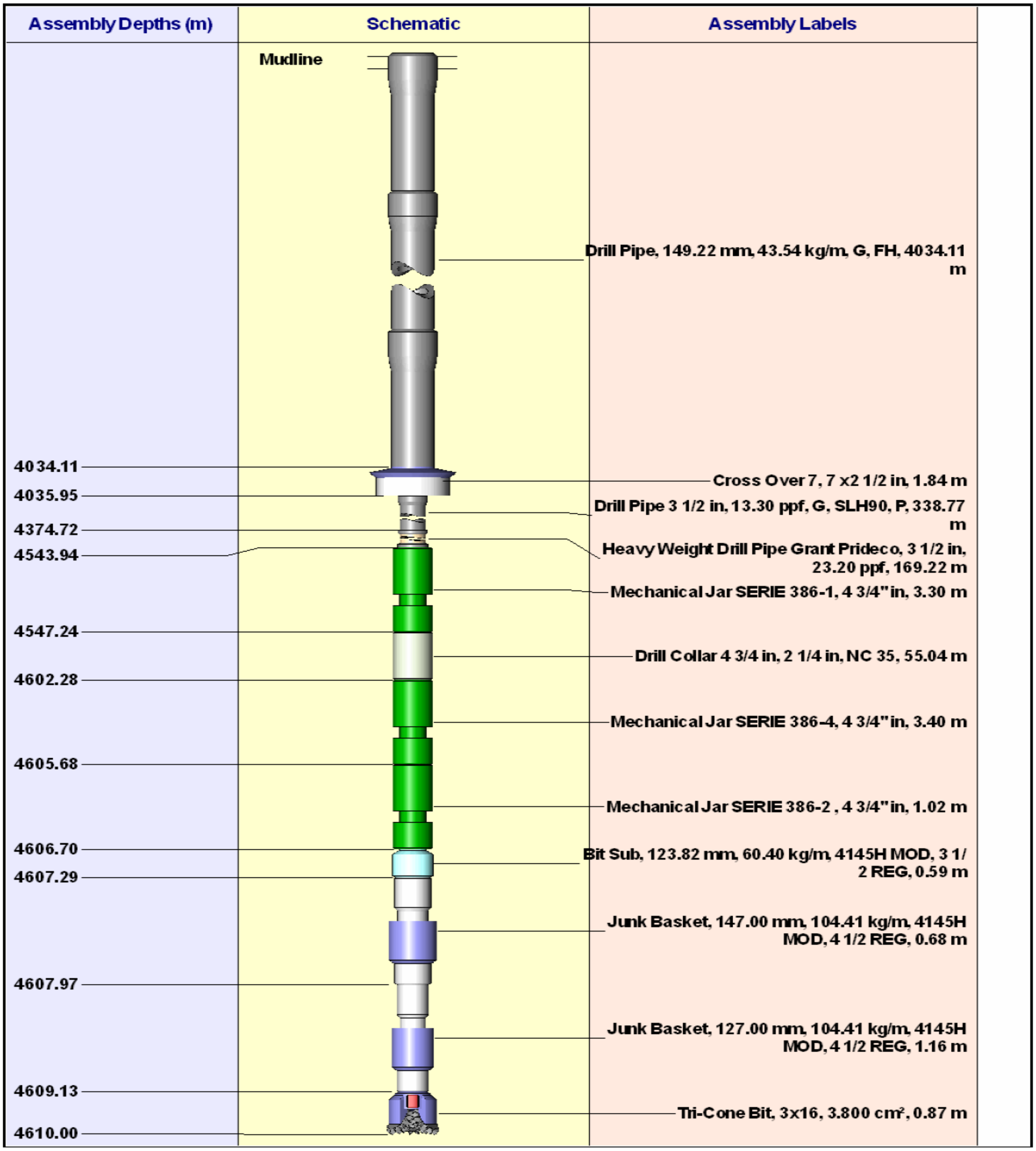


Figure 67: Drillstring and BHA Details -Real Well 2

Appendix G - Gullfaks- *Well 34/10-A-32 C*

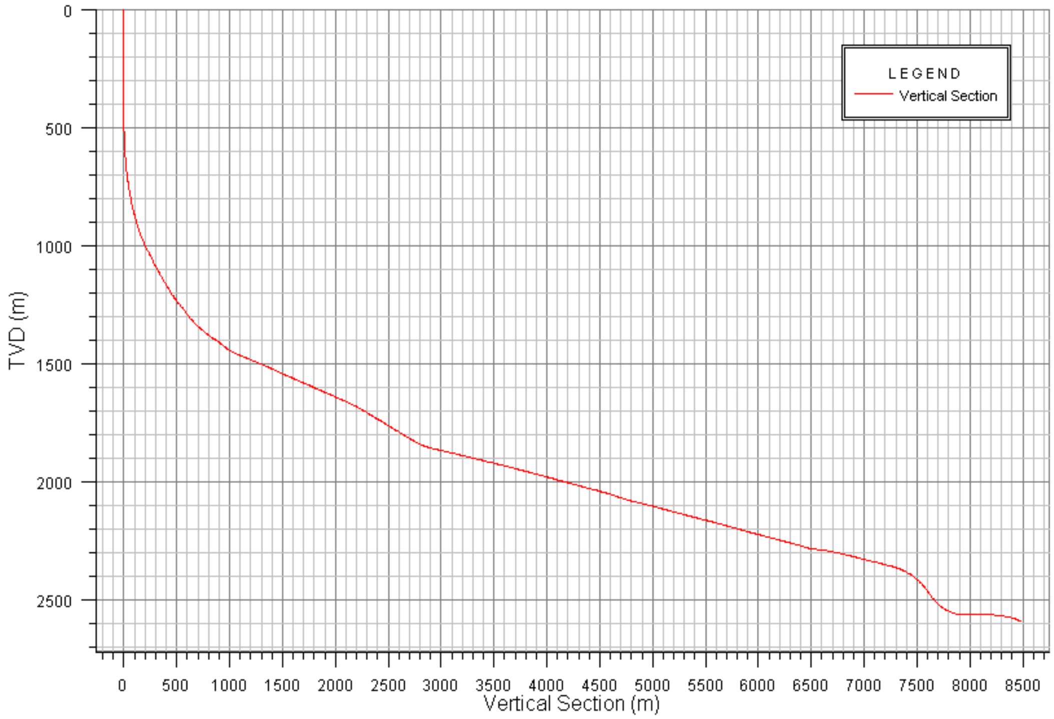


Figure 68: Vertical view Well 34/10-A-32 C

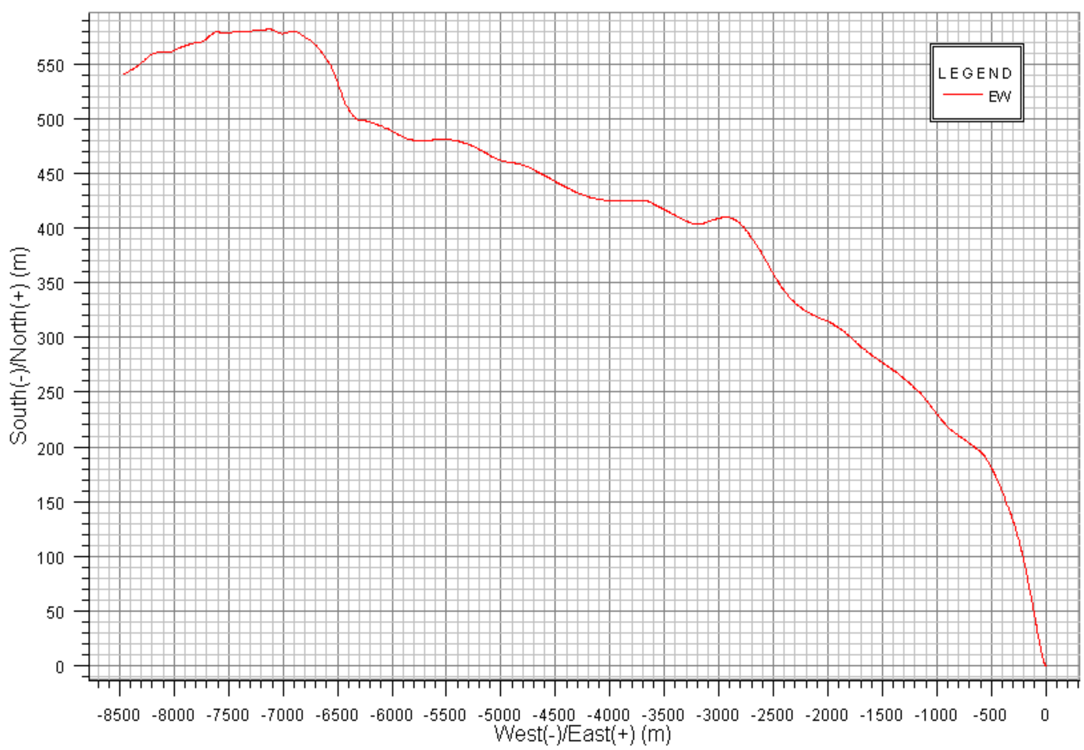


Figure 69: Planned View Well 34/10-A-32 C

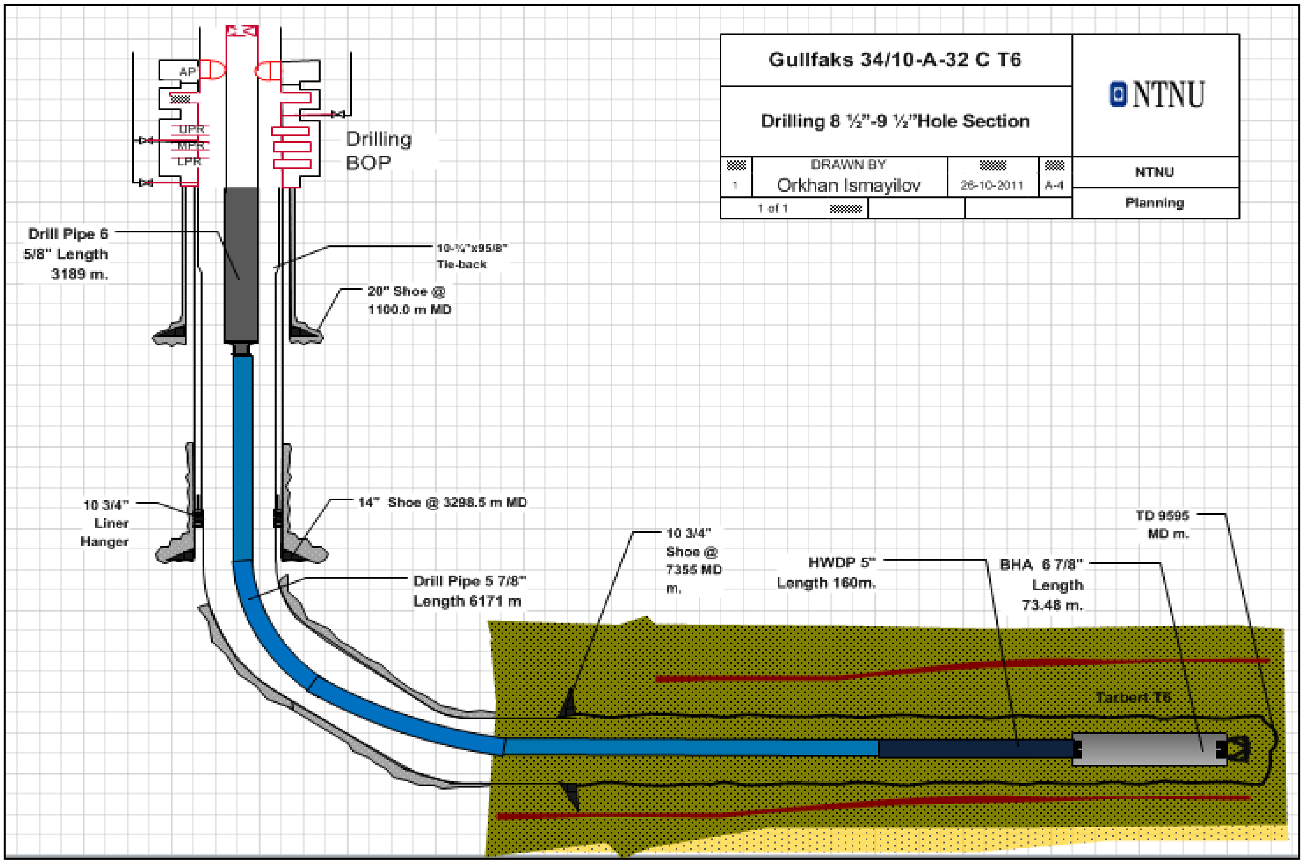


Figure 70: Drillstring and Casing Configuration[21]

Table 21: Drillstring and BHA Details -Well 34/10-A-32 C

Type	Length	Depth	Body		Stabilizer / Tool Joint				Weight	Material	Grade	Class
			OD	ID	Avg. Joint Length	Length	OD	ID				
	(m)	(m)	(mm)	(mm)	(m)	(m)	(mm)	(mm)	(kg/m)			
Drill Pipe	2 663.266	2 663.27	168.28	151.51	9.14	0.482	209.55	120.65	46.94	CS_API 5D/7	G	1
Cross Over	1.000	2 664.27	165.10	48.77					142.57	CS_API 5D/7	4145H MOD	
Drill Pipe	5 646.000	8 310.27	146.05	121.36	9.14	0.457	177.80	101.60	43.54	CS_API 5D/7	E	1
Cross Over	1.000	8 311.27	158.50	48.77					106.54	CS_API 5D/7	4145H MOD	
Drill Pipe	1 045.000	9 356.27	146.05	121.36	9.14	0.457	177.80	101.60	43.54	CS_API 5D/7	E	1
Cross Over	1.000	9 357.27	165.10	48.77					142.57	CS_API 5D/7	4145H MOD	
Heavy Weight Drill Pipe	168.520	9 525.79	127.00	76.20	9.14	1.219	165.10	77.80	74.97	CS_1340 MOD	1340 MOD	
Mechanical Jar	9.030	9 534.82	163.58	57.15					103.27	SS_15-15LC	15-15LC MOD (1)	
Drill Collar	10.000	9 544.82	165.10	76.20					147.18	CS_API 5D/7	4145H MOD	
Adjustable Stabilizer	2.972	9 547.79	171.45	44.45		0.536	200.03		132.79	CS_API 5D/7	4145H MOD	
Drill Collar	9.500	9 557.29	165.10	57.15					147.89	CS_API 5D/7	4145H MOD	
Underreamer	3.820	9 561.11	165.10	38.10					350.00	CS_API 5CT	V-150	
Non-Mag Drill Collar	18.120	9 579.23	165.10	76.20					135.87	SS_15-15LC	15-15LC MOD (1)	
Logging While Drilling	2.500	9 581.73	171.45	48.77					148.82	SS_15-15LC	15-15LC MOD (1)	
Logging While Drilling	2.540	9 584.27	171.45	48.77					138.87	SS_15-15LC	15-15LC MOD (1)	
Cross Over	3.000	9 587.27	165.10	48.77					138.55	CS_API 5D/7	4145H MOD	
Float Sub	2.000	9 589.27	170.69	60.96					148.82	CS_API 5D/7	4145H MOD	
Adjustable Stabilizer	2.972	9 592.24	171.45	44.45		0.536	200.03		132.79	CS_API 5D/7	4145H MOD	
Cross Over	2.540	9 594.78	171.69	70.10					148.82	CS_API 5D/7	4145H MOD	
Tri-Cone Bit	0.220	9 595.00	215.90						204.00			

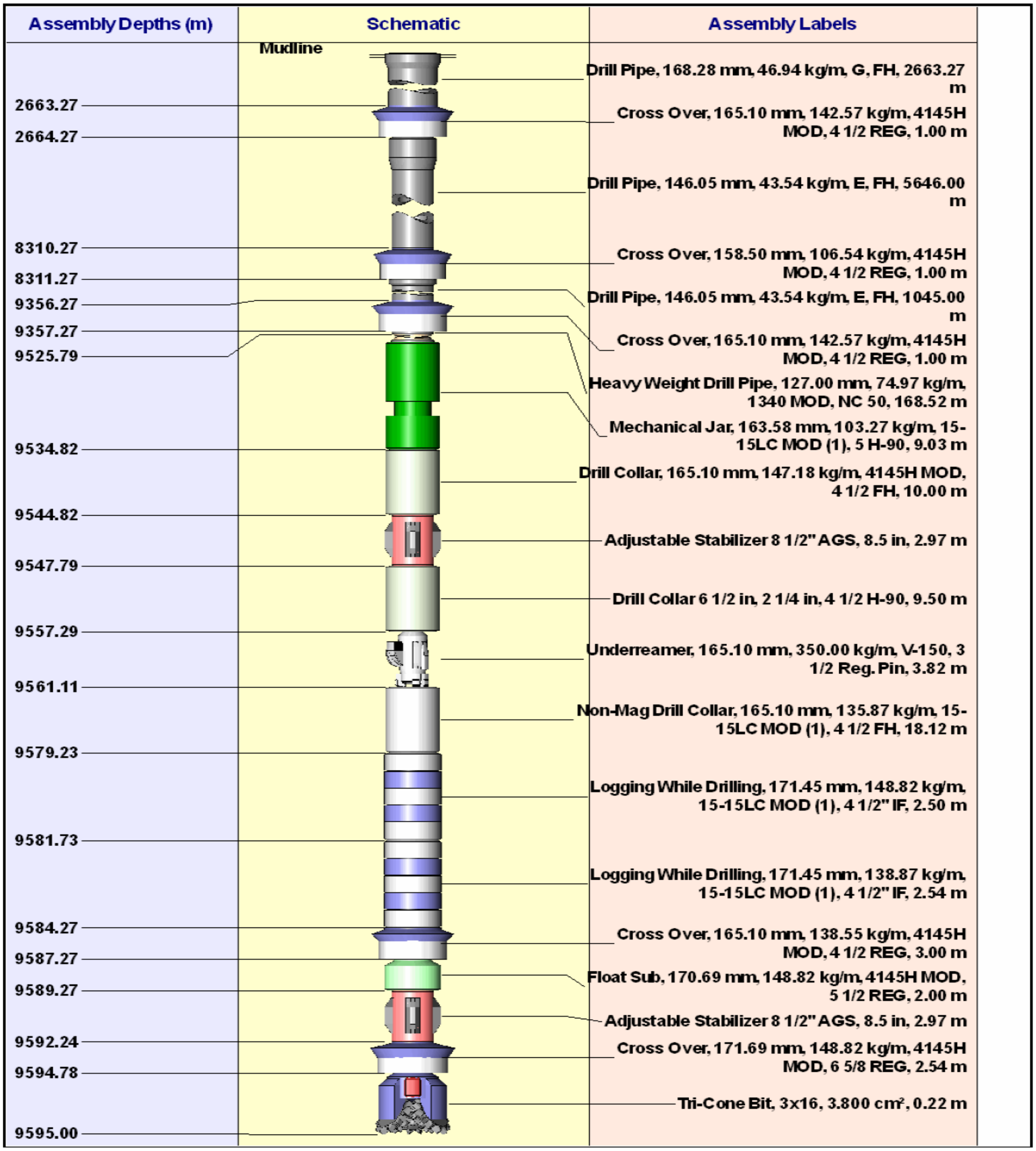


Figure 71: Drillstring and BHA Details -Well 34/10-A-32 C

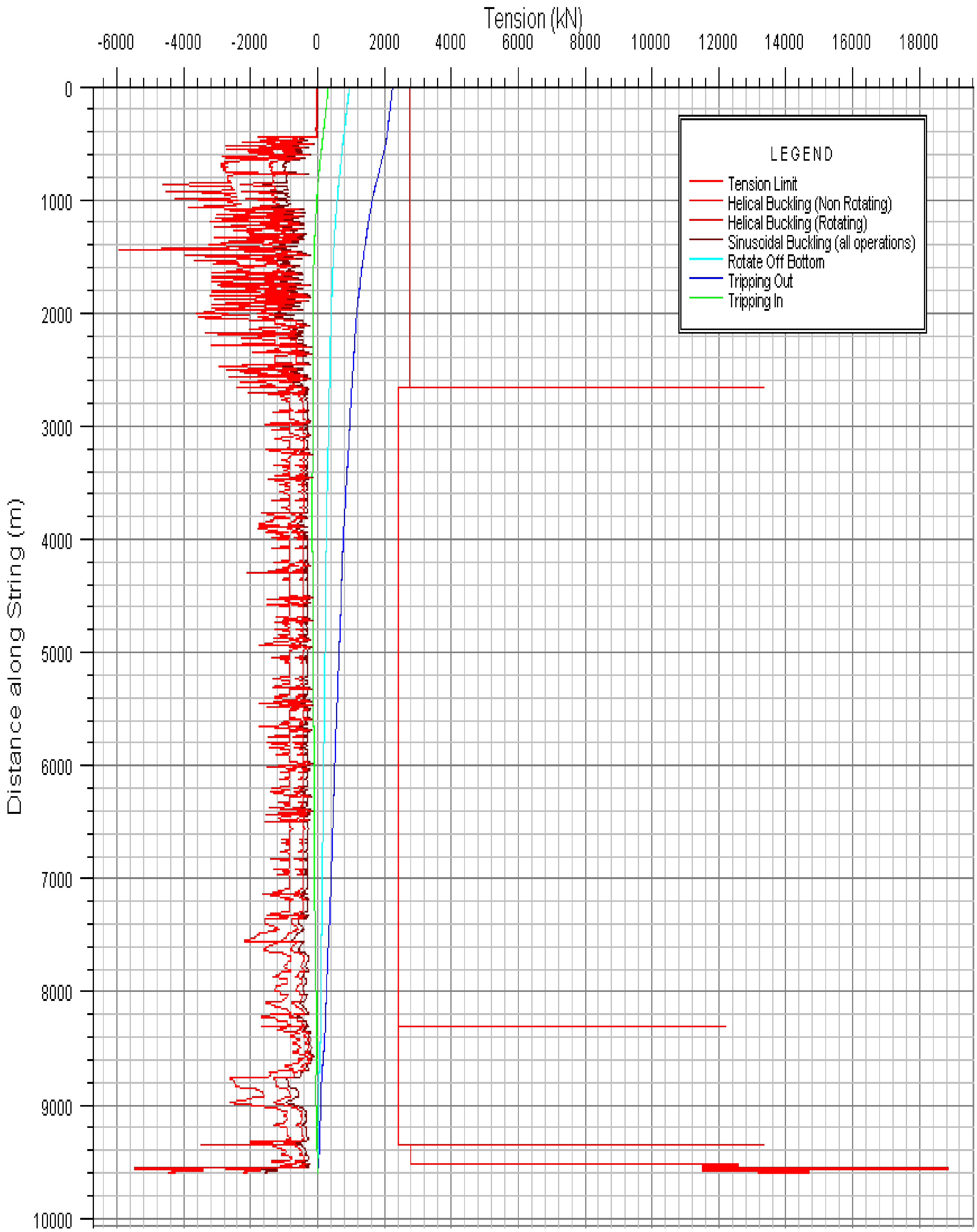


Figure 72: Effective Tension Well 34/10-A-32C

Appendix H - Matlab Script Code for Friction Coefficient back calculation

Table 22: Pick up Back Calculation Script Code at total depth

```
y=0;
x=0:0.001:0.8;
w1=148.8159943;
w2=74.97370148;
w3=43.54;
w4=46.93669891;
beta=0.792307692;
l=length(x);
k=1:l;
F1=0.*exp(x.*(abs(op1-op0)))+(beta.*w1.*L1.*((sin(angle1)-sin(angle0))./(angle1-angle0)))./10^3;
F2=F1.*exp(x.*(abs(op2-op1)))+(beta.*w2.*L2.*((sin(angle2)-sin(angle1))./(angle2-angle1)))./10^3;
F3=F2.*exp(x.*(abs(op3-op2)))+(beta.*w3.*L3.*((sin(angle3)-sin(angle2))./(angle3-angle2)))./10^3;
F4=F3+(beta.*L4.*w3.*(cos(angle4)+x.*sin(angle4)))./10^3;
F5=F4.*exp(x.*(abs(op5-op4)))+(beta.*w3.*L5.*((sin(angle5)-sin(angle4))./(angle5-angle4)))./10^3;
F6=F5.*exp(x.*(abs(op6-op5)))+(beta.*w3.*L6.*((sin(angle6)-sin(angle5))./(angle6-angle5)))./10^3;
F7=F6+(beta.*L7.*w3.*(cos(angle7)+x.*sin(angle7)))./10^3;
F8=F7.*exp(x.*(abs(op8-op7)))+(beta.*w3.*L8.*((sin(angle8)-sin(angle7))./(angle8-angle7)))./10^3;
F9=F8.*exp(x.*(abs(op9-op8)))+(beta.*w3.*L9.*((sin(angle9)-sin(angle8))./(angle9-angle8)))./10^3;
F10=F9.*exp(x.*(abs(op10-op9)))+(beta.*w3.*L10.*((sin(angle10)-sin(angle9))./(angle10-angle9)))./10^3;
F11=F10+(beta.*L11.*w3.*(cos(angle11)+x.*sin(angle11)))./10^3;
F12=F11.*exp(x.*(abs(op12-op11)))+(beta.*w3.*L12.*((sin(angle12)-sin(angle11))./(angle12-angle11)))./10^3;
F13=F12.*exp(x.*(abs(op13-op12)))+(beta.*w3.*L13.*((sin(angle13)-sin(angle12))./(angle13-angle12)))./10^3;
F14=F13+(beta.*L14.*w3.*(cos(angle14)+x.*sin(angle14)))./10^3;
F15=F14.*exp(x.*(abs(op15-op14)))+(beta.*w3.*L15.*((sin(angle15)-sin(angle14))./(angle15-angle14)))./10^3;
F16=F15+(beta.*L16.*w3.*(cos(angle16)+x.*sin(angle16)))./10^3;
F17=F16.*exp(x.*(abs(op17-op16)))+(beta.*w3.*L17.*((sin(angle17)-sin(angle16))./(angle17-angle16)))./10^3;
F18=F17.*exp(x.*(abs(op18-op17)))+(beta.*w4.*L18.*((sin(angle18)-sin(angle17))./(angle18-angle17)))./10^3;
F19=F18+(beta.*L19.*w4.*(cos(angle19)+x.*sin(angle19)))./10^3;
F20=F19.*exp(x.*(abs(op20-op19)))+(beta.*w4.*L20.*((sin(angle20)-sin(angle19))./(angle20-angle19)))./10^3;
F21=F20.*exp(x.*(abs(op21-op20)))+(beta.*w4.*L21.*((sin(angle21)-sin(angle20))./(angle21-angle20)))./10^3;
F22=F21.*exp(x.*(abs(op22-op21)))+(beta.*w4.*L22.*((sin(angle22)-sin(angle21))./(angle22-angle21)))./10^3;
F23=F22.*exp(x.*(abs(op23-op22)))+(beta.*w4.*L23.*((sin(angle23)-sin(angle22))./(angle23-angle22)))./10^3;
y(k)=F23+(beta.*L24.*w4.*(cos(angle24)+x.*sin(angle24)))./10^3;
[trash,array_position]=min(abs(y-162))
```

Table 23: Slack off- Back Calculation Script Code at total depth

```
SOy=0;
x=0:0.001:0.8;
F1=(beta.*L1.*w1.*(cos(angle1)-x.*sin(angle1)))./10^3;
F2=F1+(beta.*L2.*w2.*(cos(angle2)-x.*sin(angle2)))./10^3;
F3=F2.*exp(-x.*(abs(op3-op2)))+(beta.*w2.*L3.*((sin(angle3)-sin(angle2))./(angle3-angle2)))./10^3;
F4=F3.*exp(-x.*(abs(op4-op3)))+(beta.*w3.*L4.*((sin(angle4)-sin(angle3))./(angle4-angle3)))./10^3;
F5=F4.*exp(-x.*(abs(op5-op4)))+(beta.*w3.*L5.*((sin(angle5)-sin(angle4))./(angle5-angle4)))./10^3;
F6=F5+(beta.*L6.*w3.*(cos(angle6)-x.*sin(angle6)))./10^3;
F7=F6.*exp(-x.*(abs(op7-op6)))+(beta.*w3.*L7.*((sin(angle7)-sin(angle6))./(angle7-angle6)))./10^3;
F8=F7.*exp(-x.*(abs(op8-op7)))+(beta.*w3.*L8.*((sin(angle8)-sin(angle7))./(angle8-angle7)))./10^3;
F9=F8.*exp(-x.*(abs(op9-op8)))+(beta.*w3.*L9.*((sin(angle9)-sin(angle8))./(angle9-angle8)))./10^3;
F10=F9+(beta.*L10.*w3.*(cos(angle10)-x.*sin(angle10)))./10^3;
F11=F10.*exp(-x.*(abs(op11-op10)))+(beta.*w3.*L11.*((sin(angle11)-sin(angle10))./(angle11-angle10)))./10^3;
F12=F11.*exp(-x.*(abs(op12-op11)))+(beta.*w3.*L12.*((sin(angle12)-sin(angle11))./(angle12-angle11)))./10^3;
F13=F12+(beta.*L13.*w3.*(cos(angle13)-x.*sin(angle13)))./10^3;
F14=F13.*exp(-x.*(abs(op14-op13)))+(beta.*w3.*L14.*((sin(angle14)-sin(angle13))./(angle14-angle13)))./10^3;
F15=F14+(beta.*L15.*w3.*(cos(angle15)-x.*sin(angle15)))./10^3;
F16=F15.*exp(-x.*(abs(op16-op15)))+(beta.*w4.*L16.*((sin(angle16)-sin(angle15))./(angle16-angle15)))./10^3;
F17=F16+(beta.*L17.*w3.*(cos(angle17)-x.*sin(angle17)))./10^3;
F18=F17+(beta.*L18.*w4.*(cos(angle18)-x.*sin(angle18)))./10^3;
F19=F18.*exp(-x.*(abs(op19-op18)))+(beta.*w4.*L19.*((sin(angle19)-sin(angle18))./(angle19-angle18)))./10^3;
F20=F19.*exp(-x.*(abs(op20-op19)))+(beta.*w4.*L20.*((sin(angle20)-sin(angle19))./(angle20-angle19)))./10^3;
F21=F20.*exp(-x.*(abs(op21-op20)))+(beta.*w4.*L21.*((sin(angle21)-sin(angle20))./(angle21-angle20)))./10^3;
F22=F21.*exp(-x.*(abs(op22-op21)))+(beta.*w4.*L22.*((sin(angle22)-sin(angle21))./(angle22-angle21)))./10^3;
y(k)=F22+(beta.*L23.*w4.*(cos(angle23)-x.*sin(angle23)))./10^3;

[trash,array_position]=min(abs(y-56))
```