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Finite Element Analysis of Drillstring and Its Application on Torque and Drag Calculation

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--Abstract--

The correct calculation and analysis of torque and drag is important for well design and drilling optimization. The real-time calculated friction factor between drillstring and wellbore can be used to identify possible hole cleaning problems, stuck pipe, differential sticking, formation change and mud lubrication problems. There are a number of programs or software that calculate torque and drag both analytically or numerically. This paper introduces a practical finite element analysis (FEA) model and corresponding program, which can simulate the working behavior of drillstring during the drilling operation. The program developed in this paper can be used for torque and drag analysis in vertical, directional, horizontal, and even any other complicated wells under different drilling operational modes. In addition, given the hookload and other drilling parameters and wellbore data, the FEA program can automatically back-calculate the friction factor or coefficient between drillstring and casing or rocks. The FEA program developed in this paper was verified by analyzing hookload and torque in three wells. It has been shown the calculation of hook load is accurate, and the torque calculated by the program is acceptable. All the results from the FEA program match those from the field well. The back-calculation of friction coefficient for a well is also carried out. The FEA program will benefit in real-time simulation of drillstring, and give warning prematurely on some possible drilling operational problems.

Keywords: *Torque and drag, Application, Finite element analysis, Drilling, Drillstring, Wellbore*

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I. Introduction

Torque and drag modeling is considered as an important assessment to aid real-time drilling analysis. It predicts and prevents drilling troubles such as tight holes, cutting bed accumulations, differential sticking, etc (Fazaelizadeh et al., 2010). Mason and Chen (2007) states that T&D modeling is regarded as an invaluable process in well planning for assisting and predicting, as well as preventing drilling problems. Real-time calculated friction factor logs are used for identifying hole cleaning problems, stuck pipe, differential sticking, formation change and mud lubrication problems (Reiber et al., 1999). Excessive torque and drag in the design of a wellbore trajectory and drillstring configuration might cause severe damage to a device that turns the drillstring (top drive) capacity, drill pipe strength, and available lifting capacity. It can increase pipe fatigue, casing wear, and mechanical borehole problems, such as hole enlargement and can lead to an inability to slide. Moreover, a conventional steerable assembly might increase frictional forces, which can lead to failures in the tubular from excessive wear, bucking, and collapse (Prurapark et al., 2009). Torque and drag issues are particularly prominent in deviated and horizontal wells, due to the effects of the weight of the drillstring on the lower side of wellbore (Lenamond, 2003). Johncsik developed computer model to predict drillstring torque and drag. The principle of the predictive model is that torque and drag forces in a directional wellbore are primarily caused by sliding friction. Friction coefficients can also be determined from the field data by using the same model (Johancsik et al., 1984). Aadnoy independently developed a torque and drag model for straight sections, build-up sections, drop-off sections and side bends (Aadnoy et al., 2001). Mirhaj analyzed a shallow well with long horizontal section including side turns to see how much friction is increasing due to the bends in the wellbore based on a 3-dimentional analytical friction model (Mirhaj et al., 2010). These torque and drag models are called soft string models because they ignore any effects of tubular stiffness. This means the drillstring is represented as a heavy chain that transmits axial tension and torque caused by drillstring friction resulting from normal contact forces between the pipe and the wellbore. Although some researchers took stiffness into consideration in their models, the assumption is that the drillstring is continuous contact with the wellbore(Ho, 1988). To take into account the stiffness and the borehole-drillstring clearance effectively when calculating torque and drag, the Finite Element Method (FEM) is another choice. The rapid advance of computing power and the even more spectacular reduction in computing cost has subsequently led to more widespread use of Finite Element Analysis (FEA). FEM has been used for a number of years in the oilfield(Aslaksen et al., 2006). FEA has its beginnings as far back as 1943 when it was employed by Richard Courant who used the Ritz Method of variation calculus to analyze vibration systems. The basic concept is to subdivide a large complex structure into a finite number of sample elements, such as beam, plate, and shaft elements. In this case, a set of n second-order differential equations are obtained where n is the number of discretized degrees of freedom (Alnaser, 2002). Therefore no mater how complicated the wellbore curvature, the drillstring and the boundaries are, FEM can get the solution. No matter what kind of methods (analytical or numerical) the researchers take, the applications reflect in the form of application software. There is different working behavior under different drilling operation modes, and friction factors are obtained (Samuel, 2010). Many researchers have developed some software in which all modes have been included. TADPRO calculates the torque and drag along drilling strings or casings for various operations.

DDRAG is among the most widely used software applications in the petroleum industry. The Drillscan, 3-d software, can clearly show the forces and deformation of the drillstring, so has wide application in drilling optimization and well planning (Studer et al., 2007). BHASYS PRO addresses the statics and dynamics of the BHA in 3D wellbore, is intended for use by engineering support personnel, and is in use worldwide by Baker Hughes. Smith Bits developed the Integrated Dynamic Engineering Analysis System (IDEAS). IDEAS is a comprehensive tool that accurately predicts a drill bit's performance and behavior and how it behaves as an integral part of the total drilling system. The authors in this paper developed a practical FEA program of drillstring working behavior in different modes(Wu et al., 2011), including tripping in, tripping out, rotating off bottom, drilling forward, reaming and back reaming, sliding, and rotary steering drilling. This paper introduces the establishment of FEA model, and verifies the FEA program. Therefore a few application examples and corresponding results are presented in this paper.

II. FE Modeling Of Drillstring

2.1 Wellbore geometry and drillstring structure

Besides the common vertical wells, there are directional and horizontal wells. The advent of steerable systems has resulted in wells that are planned and drilled with complex paths involving 3-dimensional turns (as shown in Figure 1), which means both inclination angle and azimuth changeable. Therefore the calculation of torque and drag is more challenging. The drillstring consists of several drill pipes, drill collars, stabilizers and connections (as shown in Figure 2). They are under some heavy and complex dynamic loadings, caused by different sources such as bit and drillstring interactions with the formations, torque exerted by rotary table or top drive, buckling and misalignment. A finite element model has been established to simulate the complicated working behavior of drillstring.

2.2 Model of FEA

Hamilton's principle is used to derive the following dynamic equation.

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=\{F\} \qquad (1)$$

Where the vector $\{U\}$,$\{\dot{U}\}$ $\{\ddot{U}\}$ and $\{F\}$represent generalized displacement, velocity, acceleration and force in global coordinate system respectively. The matrix $\{M\}$, $\{C\}$ and $\{K\}$ represents global mass, damping and stiffness matrix respectively (Wu et al., 2011)

$$[M]^e=[M_1]^e+[M_2]^e \qquad (2)$$

2.3 External force vector

In this paper, the external force includes gravity, friction force or drag between drillstring and wellbore, and impact force between drillstring and wellbore.

2.4 Main Boundary Conditions

This paper considers the boundaries at rotary table, drill bit and stabilizers. At the rotary table, radial displacement is constrained, axial displacement and rotation around drillstring axis is released. At the bottom hole, radial displacement is constrained, axial displacement and rotation around drillstring axis is released, axial and radial force is applied, a torque around drillstring axis is also applied. At the stabilizers: radial displacement is constrained and axial displacement and rotation around drillstring axis is released.

2.5 Numerical Solution Method (Wilson- □)

General procedures:

1. Calculation in the beginning

（1）forming matrix [M], [K] and [C]

（2）giving initial α_0, $\dot{\alpha}_0$ and $\ddot{\alpha}_0$

（3）selecting time step and calculating integral constants as Eqs 3, 4

$$\theta = 1.4,\ c_1 = \frac{\theta^2 \Delta t^2}{6},\ \ c_2 = \frac{\theta \Delta t}{2},\ c_3 = 2c_2,\ c_4 = 2c_1,\ c_5 = \frac{1}{\theta}, \tag{3}$$

$$c_6 = \frac{\Delta t}{2\theta},\ c_7 = c_6(2\theta - 1),\ c_8 = \Delta t,\ c_9 = 6\frac{\Delta t^2}{2\theta},\ c_{10} = c_9(3\theta - 1) \tag{4}$$

（4）forming equivalent mass matrix Eq 5

$$\left[\breve{M}\right] = \left[M\right] + c_1\left[K\right] + c_2\left[C\right] \tag{5}$$

2. Calculation at an arbitrary time step

（1） Calculating equivalent load vector at the time $t + \theta\Delta t$ as Eq 6

$$\left\{\tilde{F}_{t+\theta\Delta t}\right\} = \left\{F_{t+\theta\Delta t}\right\} - \left[K\right]\left(\left\{a_t\right\} + c_3\left\{\dot{a}_t\right\} + c_4\left\{\ddot{a}_t\right\}\right) - \left[C\right]\left(\left\{\dot{a}_t\right\} + c_2\left\{\ddot{a}_t\right\}\right) \tag{6}$$

（2） Solving acceleration $\ddot{a}_{t+\theta\Delta t}$ at the time $t + \theta\Delta t$ according to Eq 7.

$$\left[\breve{M}\right]\left[\ddot{a}_{t+\theta\Delta t}\right] = \left[F_{t+\theta\Delta t}\right] \tag{7}$$

3. Calculating displacement $a_{t+\theta\Delta t}$ (Eq 8) ,velocity $\dot{a}_{t+\theta\Delta t}$ (Eq 9) and acceleration $\ddot{a}_{t+\theta\Delta t}$ (Eq 10) at the time $t + \Delta t$

$$\left\{a_{t+\Delta t}\right\} = \left\{a_t\right\} + c_8\left\{\dot{a}_t\right\} + c_9\left\{\ddot{a}_{t+\theta\Delta t}\right\} + c_{10}\left\{\ddot{a}_t\right\} \tag{8}$$

$$\left\{\dot{a}_{t+\Delta t}\right\} = \left\{\dot{a}_t\right\} + c_6\left\{\ddot{a}_{t+\theta\Delta t}\right\} + c_7\left\{\ddot{a}_t\right\} \tag{9}$$

$$\left\{\ddot{a}_{t+\Delta t}\right\} = c_5\left\{\ddot{a}_{t+\theta\Delta t}\right\} + (1 - c_5)\left\{\ddot{a}_t\right\} \tag{10}$$

4. Repeating steps 2 and 3

III. Modeling Of Torque And Drag

The normal force Fn is very important in calculation of torque and drag (as shown in Figure3). However the finite element method/program can calculate the contact force or normal force automatically. After the normal contact force was obtained, the axial drag and torque can be obtained easily (Eqs 11, 12) if axial and tangential friction coefficient is given respectively. The following is an example for upward movement of a drillstring (tripping out).

$$F_f = \mu_a \cdot F_n \tag{11}$$

$$T_f = \mu_t \cdot F_n \cdot r \tag{12}$$

If the movement of drillstring is downward (tripping in, drilling), the direction of the friction force or drag is opposite compared to the situation in Figure 3.

IV. FEA Program

A FEA program was developed for analyzing working behavior and calculating torque and drag based on above models using FORTRAN. Input dada includes drill string structure, wellbore geometry, and control parameters. Output includes torque, drag, friction coefficient, hook load, contacting nodes, translation and rotation at any node. The main calculation flow includes: (1)Read in all data from input files;(2)Initialize all matrixes and vectors;(3) Apply boundaries and solve dynamic equations;(4) Repeat (3) till the solution is converged;(5) Output results.

V. Applications

5.1 Horizontal well drilling example

This is a complex example (azimuth=0), which is about horizontal well drilling (as shown in Figure 4). The well profile is from field survey data, and the drillstring is a little different from the field data. The length of the whole drillstring is 3351m. Figure 5 shows the relations between hookload calculated by the FEA program and calculation times.

5.2 Extended reach well drilling example

This is more complex example, and is a very good example for friction analysis as all different sections of well geometry exist including straight inclined, curved and horizontal sections. Figure 8 shows the geometry of the well under consideration with casing shoe positions.

5.3 Directional well

This is another application example in a directional well (as shown in figure 10). From 2200m the wellbore inclination begins to increase and reach to 30 degree at 3251m depth. The drillstring component (BHA) did not change from 2200 m, and MW was around 1350 kg/m3.

5.4 Back-calculation of friction coefficient

If we know the hook load measured on the surface, and then we can back-calculate the friction coefficient or factor using the FEA program (as shown in Figure12). This involves using optimal method to get an appropriate coefficient when the calculated hook load is close to the known hook load (for example, the field hook load).

5.5 Figure Explanations And Analysis Of Results

Figure5 shows the hook load becomes stable gradually with time increase. Figures 6 and 7 indicate that the solution from FEA is closer to the average of the field data under the normal condition. Figure 9 shows that the hook load from FEA matches that from the field as a whole. Figure11 shows the comparison of hookload between field data and the FEA program in the paper. The comparison just covers the section from 2200m to 3251m, which is the inclined part of the well. From Figure 12 we know the changing trend of friction coefficient is the same as a whole under different element length. From the forgoing analysis, the FEA program of drill string works well in the calculation of torque and drag. However there is much work to do to analyze the real behavior of the whole drillstring during the oil well drilling operation. For example, the boundaries on the bit are very complicated and that will be focused on in the future.

VI. Conclusions

The FEA program was verified by analyzing hookload and torque in three wells. It has been shown the calculation of hook load is accurate, and the torque calculated by the program is acceptable. All the results from the FEA program match those from the field well. The back-calculation of friction coefficient for a well is also carried out. The FEA program will benefit in real-time simulation of drillstring, and give warning prematurely on some possible drilling operational problems.

VII. Acknowledgement

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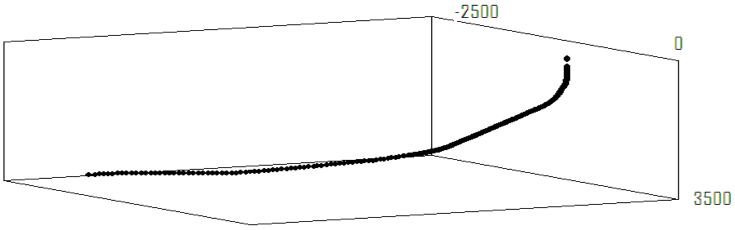


[16].

Figure 1. 3-dimensional well profile

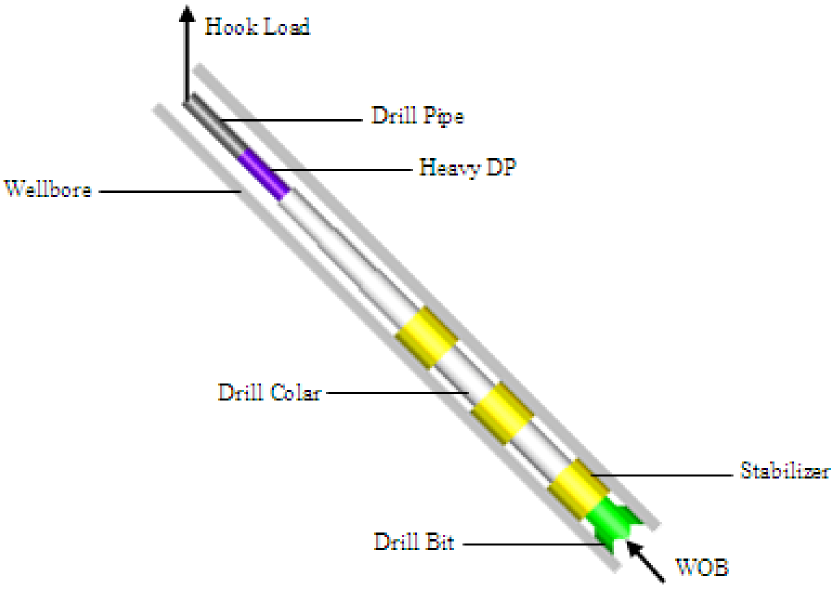


Figure 2. Typical drill string configuration

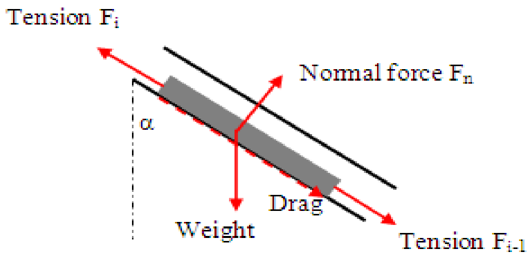


Figure 3. The forces applied on an element of drill string

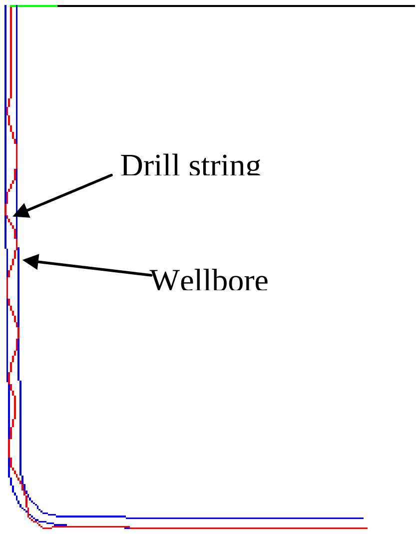


Figure 4. FEA of drillstring while horizontal well drilling

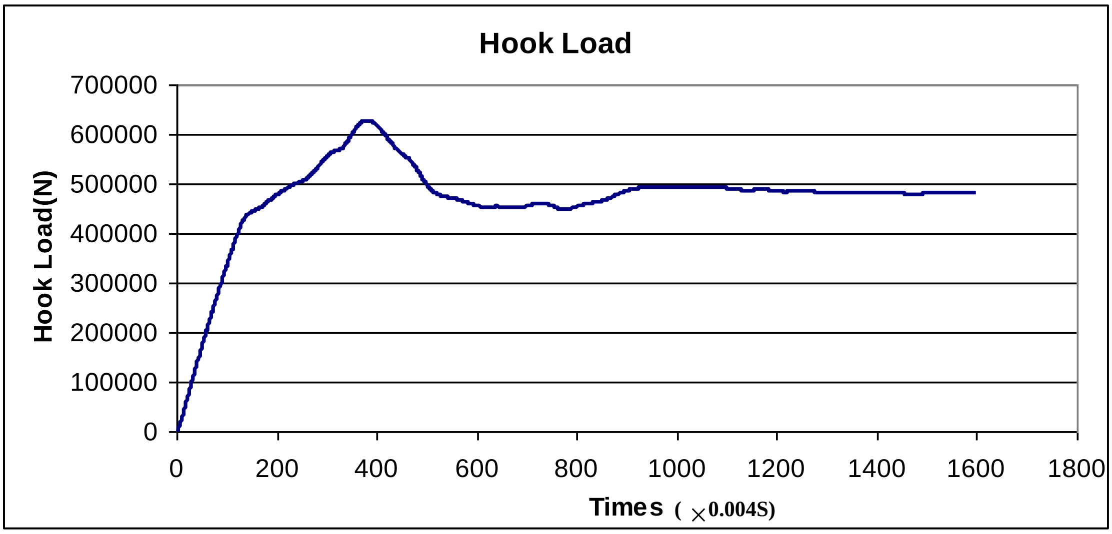


Figure 5. The calculated hook load versus simulation time

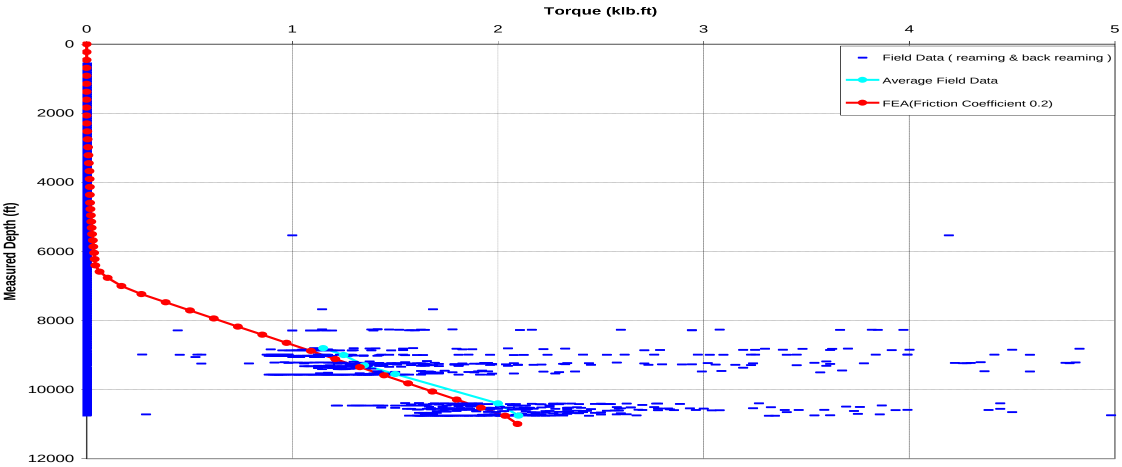


Figure 6. The calculated torque versus measured depth

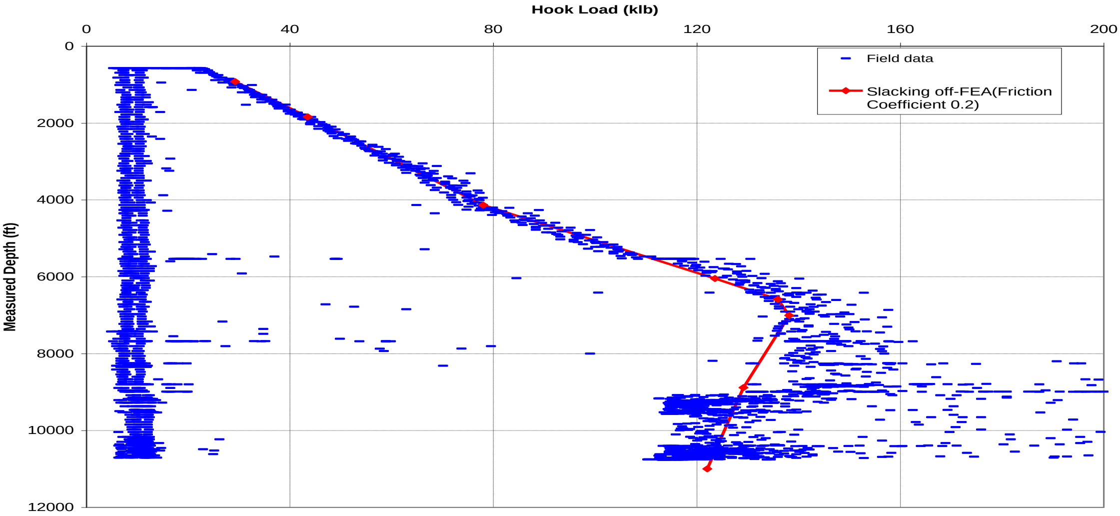


Figure 7. The calculated hook load versus measured depth

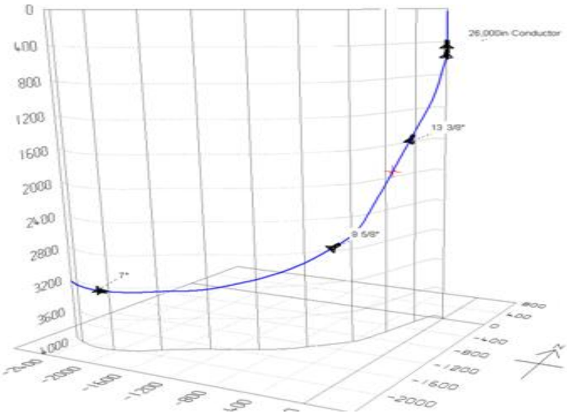


Figure 8. Another 3D wellbore path

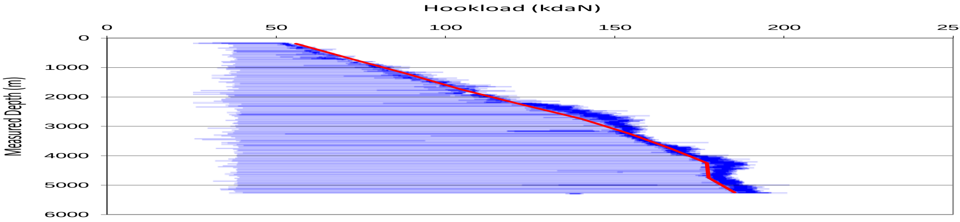


Figure 9. Comparison between field and finite element hook-load data with using friction coefficient=0.2 while tripping-out

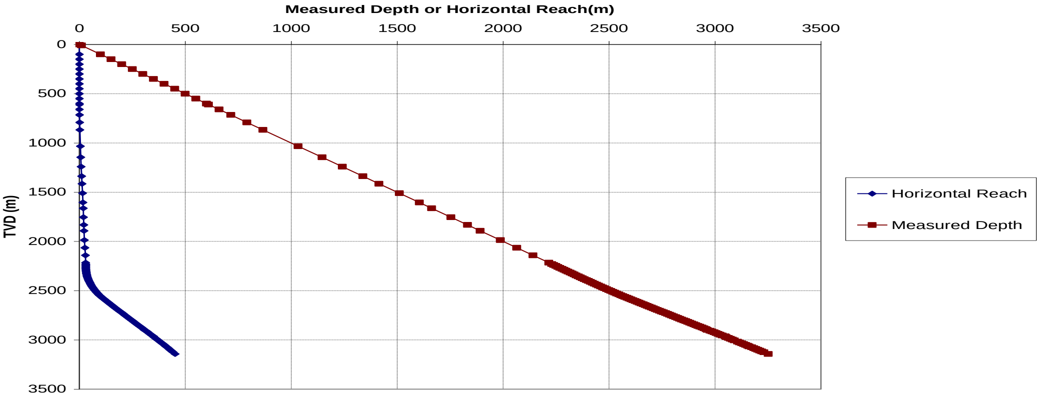
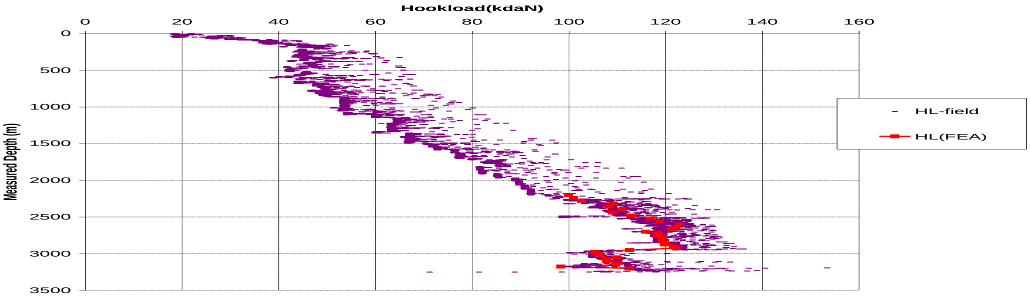
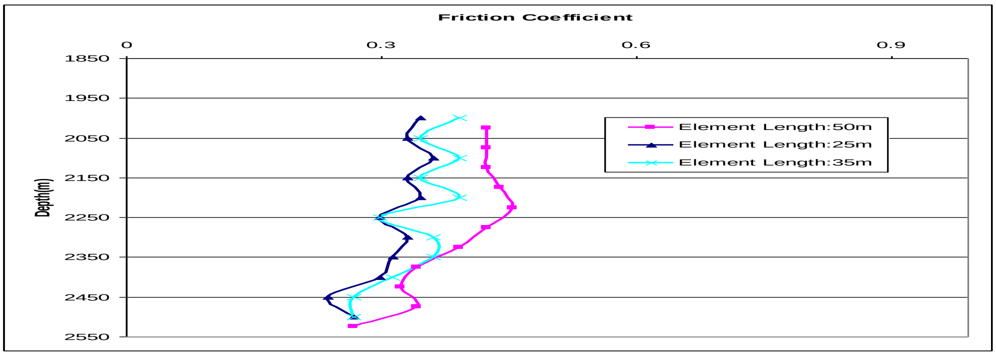


Figure 10. the wellbore geometry of the directional well.



Figures 11. comparison of hookload between field data and FEA program.



Figures 12. Trend comparison of friction coefficients under different element length (tripping out)