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REAL-TIME SOFTWARE TO ESTIMATE FRICTION COEFFICIENT AND DOWNHOLE WEIGHT ON BIT DURING DRILLING OF HORIZONTAL WELLS

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ABSTRACT

The increasing complexity and higher drilling cost of horizontal wells demand extensive research on software development for the analysis of drilling data in real-time. In extended reach drilling, the downhole weight on bit (WOB) differs from the surface seen WOB (obtained from on an off bottom hookload difference reading) due to the friction caused by drill string movement and rotation in the wellbore. The torque and drag analysis module of a user-friendly real-time software, Intelligent Drilling Advisory system (IDAs) can estimate friction coefficient and the effective downhole WOB while drilling. IDAs uses a 3-dimensional wellbore friction model for the analysis. Based on this model the forces applied on a drill string element are buoyed weight, axial tension, friction force and normal force perpendicular to the contact surface of the wellbore. The industry standard protocol, WITSML (Wellsite Information Transfer Standard Markup Language) is used to conduct transfer of drilling data between IDAs and the onsite or remote WITSML drilling data server.[1]

IDAs retrieves real-time drilling data such as surface hookload, pump pressure, rotary RPM and surface WOB from the data servers. The survey data measurement for azimuth and inclination versus depth along with the retrieved drilling data, are used to do the analysis in different drilling modes, such as lowering or tripping in and drilling. For extensive analysis the software can investigate the sensitivity of friction coefficient and downhole WOB on user-defined drill string element lengths. The torque and drag analysis module, as well as the real-time software, IDAs has been successfully tested and verified with field data from horizontal wells drilled in Western Canada. In the lowering mode of drilling process, the software estimates the overall friction coefficient when the drill bit is off bottom. The downhole WOB estimated by the software is less than the surface measurement that the drillers used during drilling. The study revealed verification of the software by comparing the estimated downhole WOB with the downhole WOB recorded using a downhole measuring tool.

INTRODUCTION

The drilling engineers and researchers have been coordinating extensive research works over the years to develop efficient real-time engineering software for the oil and gas industry. The

*previously with the University of Calgary engineering analysis tools or software have been developed by many oil and gas companies and some software providers to fulfill the growing demand of a more digital oilfield. The Intelligent Drilling Advisory system (IDAs) is a real-time drilling engineering tool (1) to provide meaningful analysis of both static and real-time drilling data using different engineering modules included into the system. IDAs uses a secure oil and gas industry standard, WITSML (Well Site Information Transfer Standard Markup Language) (2) to retrieve drilling data from the remote or on-site data server. IDAs supports WITSML standard version 1.3.1 which is currently the most stable and widely implemented version used in oil and gas industry.

The link between rig site and the Intelligent Drilling Advisory system (IDAs) is shown in Fig. 1 (3). The drilling data is transferred from the rig site to a WITSML server by a wellsite service company as shown in Fig. 1. The application software needs proper server authentication to retrieve drilling data from a WITSML server using web service protocol. After successful server authentication, IDAs retrieves drilling operational data from WITSML server to the office location for visualization, collaboration and analysis of the drilling operational data. The retrieved drilling data, analytical results and warning/alarm are displayed in the office or drilling center for better decision making by the drilling engineers. The results, warning or alarm and/or decisions made by engineers can be sent back to rig site and displayed on a real-time monitor for the rig operators/drillers to optimize the drilling operations. Five engineering modules are currently included into the software to provide meaningful drilling data analysis. The torque and drag analysis module for horizontal wells, is one of the most important modules to analyze the drilling data in real time and helps for better decision-making to optimize the drilling process and increase overall drilling efficiency.

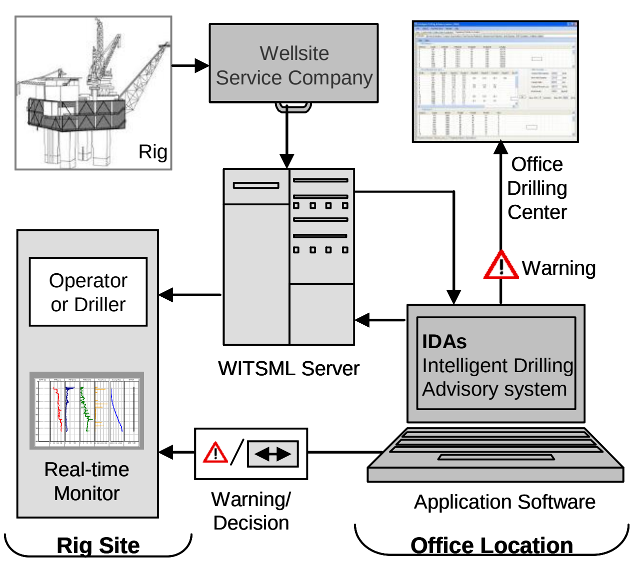


FIGURE 1 POTENTIAL SCENARIO BETWEEN RIG SITE AND IDAS

The weight on bit (WOB) is the amount of downward weight or force exerted on the drill bit and obtained from an off bottom hookload difference reading. In this article, the surface measurement of WOB is the input drilling data retrieved from the WITSML server to the system (IDAs) for analysis and expressed as 'SWOB'. In directional drilling, SWOB usually differs from the actual downhole measurement of WOB (DWOB) due to friction caused by drill string movement and rotation in the wellbore. IDAs uses a real-time wellbore friction models in the torque and drag modules to estimate the friction coefficient and DWOB during drilling of horizontal wells.

The wellbore friction model and its application into IDAs for data analysis are briefly discussed in the following sections. In addition, the sensitivity analysis of the friction coefficient and downhole WOB on the user-defined constant drill string element length is discussed herein.

WELLBORE FRICTION MODEL

The wellbore friction models (4, 5, 6) were developed by considering an element of the drill string in the wellbore filled with drilling fluid. The forces considered on the drill string element are buoyed weight, axial tension, friction force and normal force perpendicular to the contact surface of the wellbore as shown in Fig. 2.

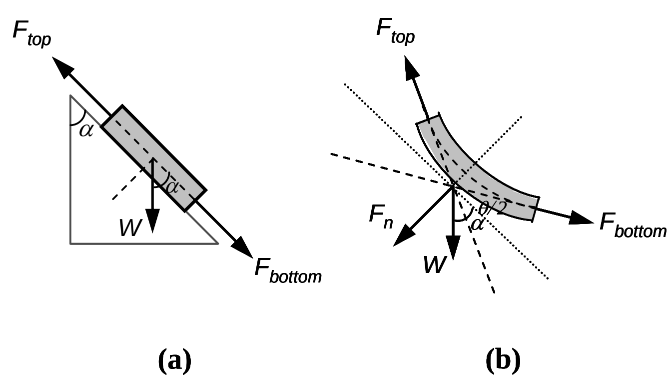


FIGURE 2 FORCE BALANCE ON DRILLSTRING ELEMENT

Fig. 2 (a) and Fig. 2 (b) represent the drill string element with straight section and curved section, respectively. In these figures, F_{top} and F_{bottom} are axial forces, F_n is net normal force acting on element and α is inclination angle. The buoyed weight of drill string element is,

$$W = \beta w \Delta L \tag{1}$$

Where, β is buoyancy factor, w is the unit weight of drill string element and ΔL is the length of the element. When the inside and outside of the drill pipe are submerged in the same fluids, the estimated buoyancy factor is (7),

$$\beta = 1 - \frac{\rho_{fluid}}{\rho_{pipe}} \tag{2}$$

Here, ρ_{fluid} and ρ_{pipe} are the density of drilling fluid and drill pipe, respectively. Eq. (2) is valid both for vertical and deviated wells.

The following equations represent the real-time wellbore friction model for straight and curved sections of a drill string element when the bit is used off-bottom to estimate the friction coefficient and on-bottom to estimate effective the downhole WOB.

When the Bit is Off-bottom

For straight inclined section, the force balance (4, 5) on a drill string element when the bit is off-bottom:

$$F_{top} = \beta w \Delta L \left(\cos\alpha - \mu \sin\alpha\right) + F_{bot} \tag{3}$$

For a curved section in tension, the force balance (4, 5) on a drill string element:

$$F_{top} = \beta w \Delta L \begin{bmatrix} \left(\dfrac{\sin\alpha_{top} - \sin\alpha_{bot}}{\alpha_{top} - \alpha_{bot}}\right) \\ + \mu \left(\dfrac{\cos\alpha_{top} - \cos\alpha_{bot}}{\alpha_{top} - \alpha_{bot}}\right) \end{bmatrix} + F_{bot} \left(e^{-\mu|\theta|}\right) \tag{4}$$

The dogleg angle, θ is the absolute change of direction which depends on both the wellbore inclination, α and azimuth, φ (3):

$$\cos\theta = \sin\alpha_{top} \sin\alpha_{bot} \cos(\varphi_{top} - \varphi_{bot}) + \cos\alpha_{top} \cos\alpha_{bot} \tag{5}$$

For a curved section in compression, the force balance (6) on a drill string element:

$$F_{top} = (\beta w \Delta L)\left[\cos\left(\frac{\alpha_{top} + \alpha_{bot}}{2}\right)\right] - \mu F_n + F_{bot} \tag{6}$$

The net normal force acting on the element (6):

$$F_n = \left(\left[F_b \left(\varphi_{top} - \varphi_{bot}\right) \left\{ \sin\left(\frac{\alpha_{top} + \alpha_{bot}}{2}\right) \right\} \right]^2 + \begin{bmatrix} \left\{ F_b \left(\alpha_{top} - \alpha_{bot}\right) \right\} \\ + \left\{ (\beta w \Delta L) \sin\left(\dfrac{\alpha_{top} + \alpha_{bot}}{2}\right) \right\} \end{bmatrix}^2 \right)^{1/2} \tag{7}$$

When the Bit is On-bottom

For a straight inclined section, the force balance on a drill string element when the bit is on-bottom and drilling mode:

$$F_{top} = \beta w \Delta L \left(\cos\alpha - \mu \sin\alpha\right) + \left(F_{bot} - DWOB\right) \tag{8}$$

For a curved section in tension, the force balance on a drill string element:

$$F_{top} = \beta w \Delta L \begin{bmatrix} \left(\dfrac{\sin\alpha_{top} - \sin\alpha_{bottom}}{\alpha_{top} - \alpha_{bottom}}\right) \\ + \mu \left(\dfrac{\cos\alpha_{top} - \cos\alpha_{bot}}{\alpha_{top} - \alpha_{bottom}}\right) \end{bmatrix} + (F_{bot} - DWOB)\left(e^{-\mu|\theta|}\right) \tag{9}$$

For a curved section in compression, the force balance on a drill string element:

$$F_{top} = \beta w \Delta L \left[\cos\left(\frac{\alpha_{top} + \alpha_{bot}}{2}\right)\right] - \mu F_n + \left[F_{bot} - DWOB\right] \tag{10}$$

REAL TIME DATA ANALYSIS USING IDAS

Drilling Data from Horizontal Well

The torque and drag stand-alone engineering tool on IDAs with wellbore friction models, has been used to retrieve drilling data of a horizontal well drilled in Western Canada using a remote WITSML server. The well geometry of the well based on the horizontal departure and measured depth vs. true vertical depth (TVD) is shown in Fig. 3. In this report, IDAs has analyzed the horizontal section from 2800m to 3500m to estimate friction coefficient, as well as the DWOB from the hook load measurement. For the analysis IDAs retrieves time-based high frequency (1 second) drilling data of the Western Canada well. The surface hook load, pump pressure, rotary RPM, surface WOB (SWOB), time, measured bit depth and hole depth are the input drilling data retrieved from the WITSML server as shown in Fig. 4. In this figure, the 'DEPTH' chart shows two sections with almost the same measurements for hole and bit depths when and rotary speeds are around 60 rpm which can be seen in the 'RPM' chart. The corresponding field measurements of surface hook load, pump pressure and SWOB are visualized in 'HK LOAD', 'SPP' and 'WOB' charts, respectively. These two sections represent the on-bottom rotating drilling operations. The information on the drill string specification (length and diameters) and bottom hole assembly (BHA) required for this analysis, are downloaded from the corresponding Electronic Tour Sheet (ETS) on the data server to IDAs, and this interface is shown in Fig. 5. The survey data measurement for azimuth and inclination versus depth, density of drilling fluid and pipe are also downloaded from the data server.

Estimation of Friction Coefficient and DWOB

The time based estimation of friction coefficient and downhole WOB using IDAs for the first drilling section of Fig. 4 is shown in Fig. 6. For this section, the bit touched the bottom of the hole to ready for drilling at 3225.71m. IDAs estimates the off bottom friction coefficient at bit depth of 3225.7m which is just the above depth before drilling is initiated. The estimated off bottom friction coefficient 0.13, is used for the on-bottom analysis during drilling from 3225.71m to 3231.49m as shown in Fig. 6.

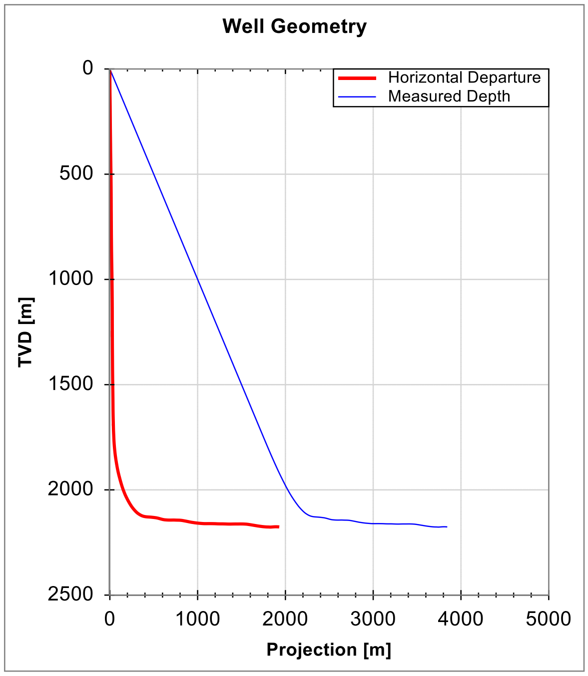


FIGURE 3 WELL GEOMETRY OF HORIZONTAL WELL

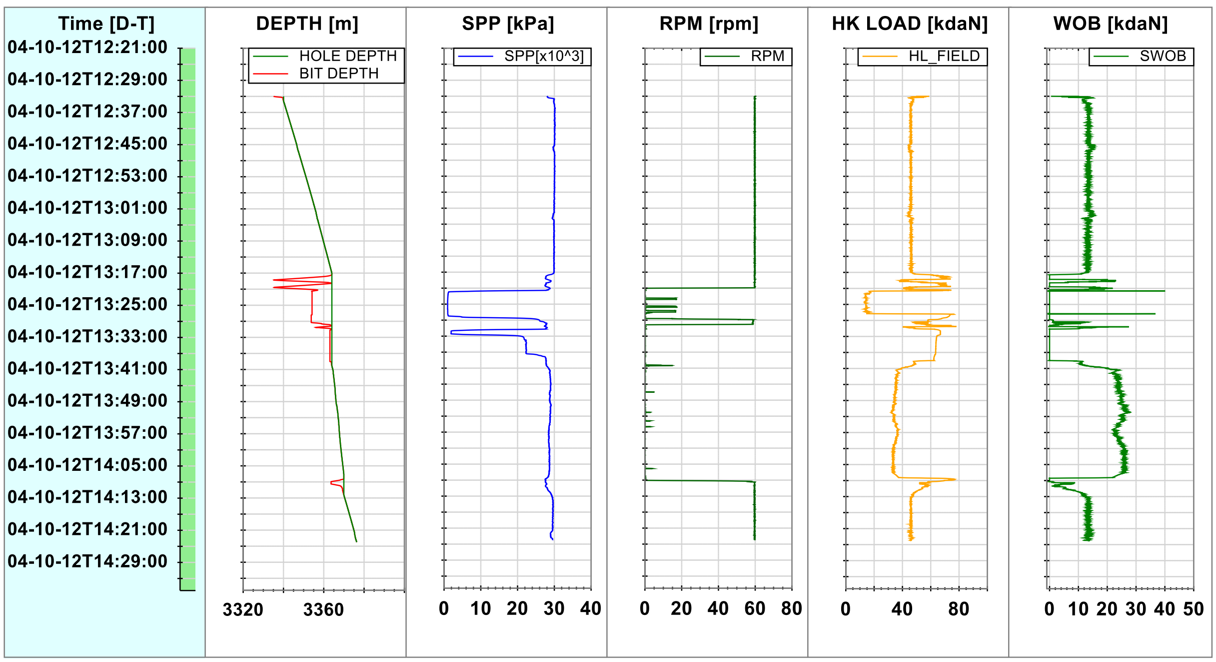
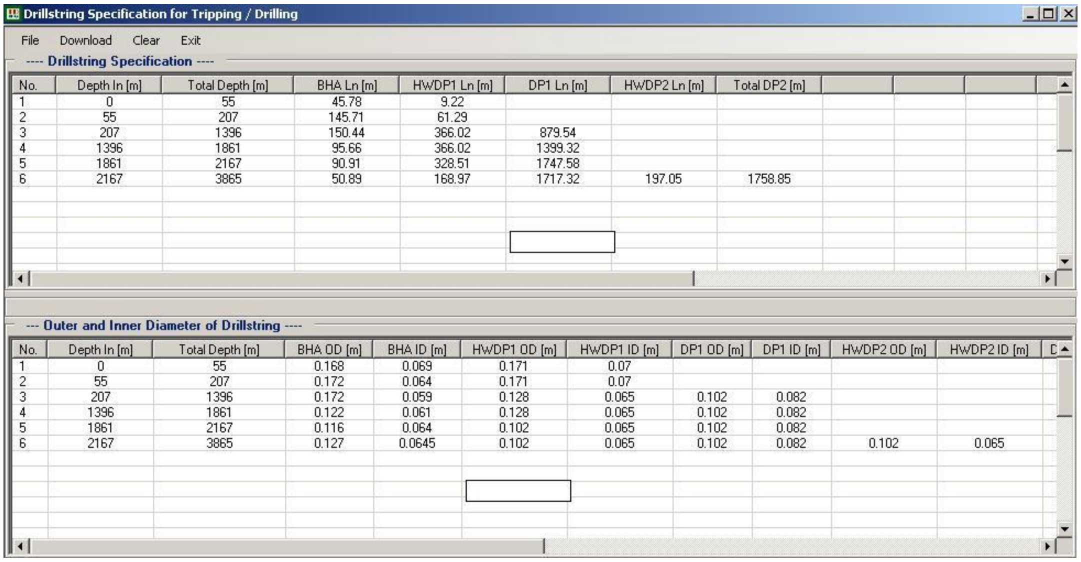


FIGURE 4 HIGH FREQUENCYTIME BASED DRILLING DATA FROM WITSML SERVER



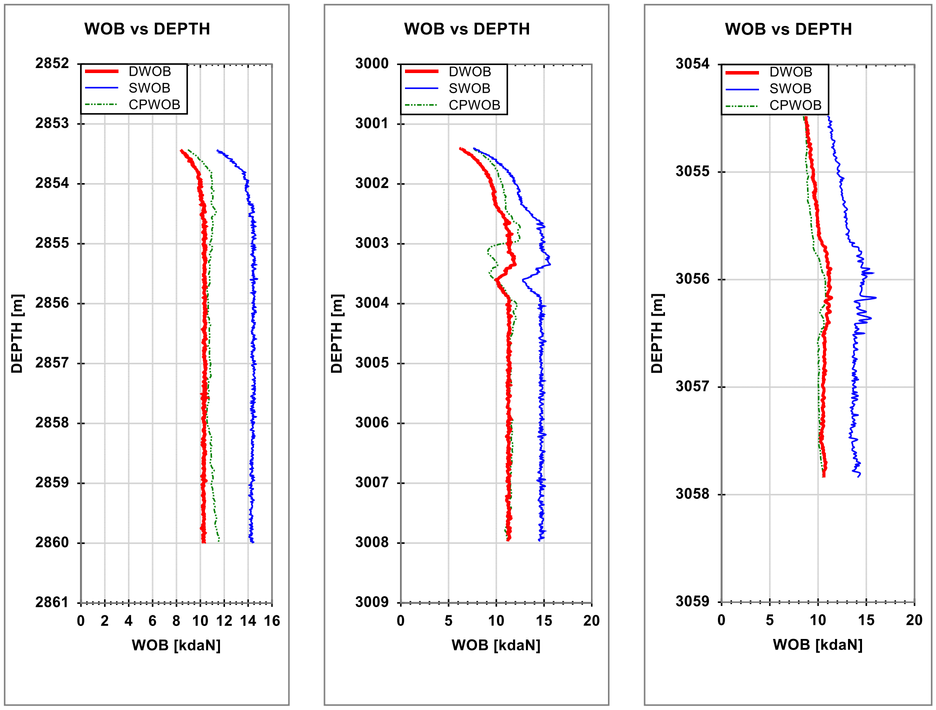
No.	Depth In [m]	Total Depth [m]	BHA Ln [m]	HWDP1 Ln [m]	DP1 Ln [m]	HWDP2 Ln [m]	Total DP2 [m]
1	0	55	45.78	9.22			
2	55	207	145.71	61.29			
3	207	1396	150.44	366.02	879.54		
4	1396	1861	95.66	366.02	1399.32		
5	1861	2167	90.91	328.51	1747.58		
6	2167	3865	50.89	168.97	1717.32	197.05	1758.85

No.	Depth In [m]	Total Depth [m]	BHA OD [m]	BHA ID [m]	HWDP1 OD [m]	HWDP1 ID [m]	DP1 OD [m]	DP1 ID [m]	HWDP2 OD [m]	HWDP2 ID [m]
1	0	55	0.168	0.069	0.171	0.07				
2	55	207	0.172	0.064	0.171	0.07				
3	207	1396	0.172	0.059	0.128	0.065	0.102	0.082		
4	1396	1861	0.122	0.061	0.128	0.065	0.102	0.082		
5	1861	2167	0.116	0.064	0.102	0.065	0.102	0.082		
6	2167	3865	0.127	0.0645	0.102	0.065	0.102	0.082	0.102	0.065

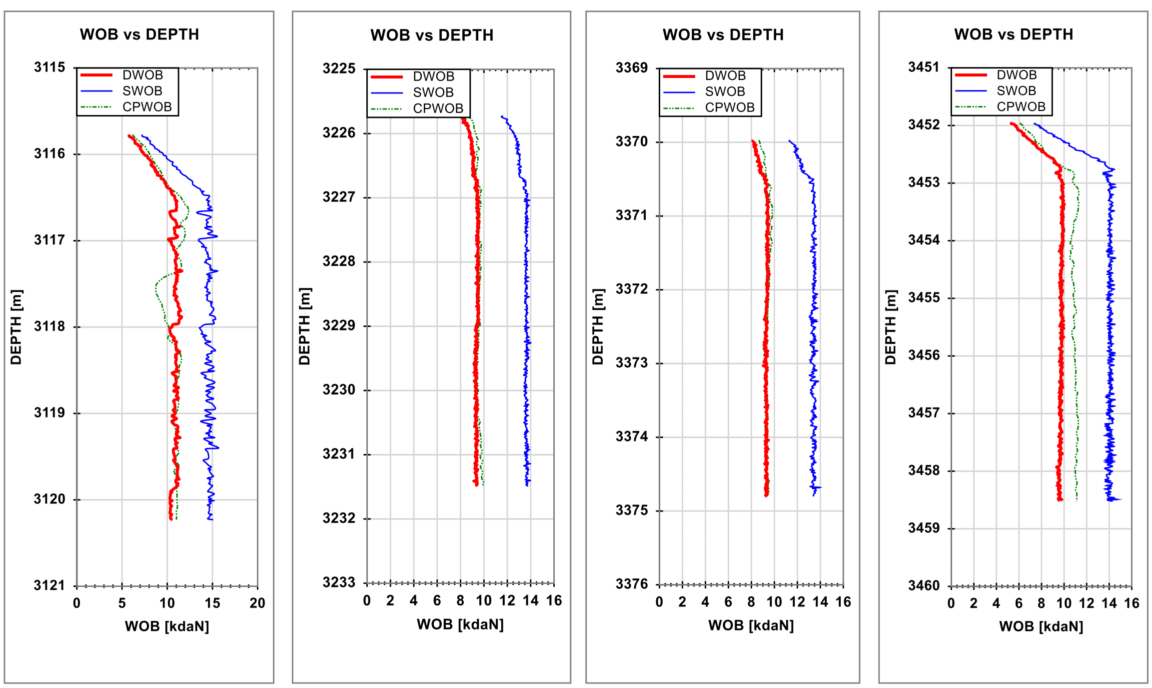
FIGURE 5 DRILL STRING SPECIFICATION REQUIRED FOR THE ANALYSIS

FIGURE 6 TIME BASED ANALYSIS TO ESTIMATE FRICTION COEFFICIENT AND DOWNHOLE WOB

There are significant increase in the standpipe pressure and a decrease in the hook load as shown in Fig. 4 and Fig. 6 when the bit is on-bottom and starts drilling. In the 'WOB' chart of Fig. 6, 'DWOB' is the estimated downhole WOB using IDAs, 'SWOB' is the field surface WOB retrieved from the WITSML server and 'CPWOB' is the downhole WOB recorded by a downhole measuring tool. The analysis at this horizontal section indicates that the effective DWOB is significantly less than the surface WOB applied in the field (DWOB is about 68% of SWOB). The corresponding depth based analysis for down hole WOB and the results from some other drilled sections are shown in Fig. 7.



(a) Drilled depth: 2852m – 2860m (b) 3001m – 3008m (c) 3054m – 3058m



(d) 3115m – 3120m (b) 3225m – 3231m (c) 3369m – 3375m (d) 3451m – 3458m

FIGURE 7 DEPTH BASED ANALYSIS TO ESTIMATE DOWNHOLE WOB

According to Fig. 7, the percentage of estimated downhole WOB over surface WOB ranges within values from 65% to 75%. The estimated friction coefficient from the horizontal drilling depth of 2850m to around 3450m is shown in Fig. 8. The average friction coefficient estimated using IDAs for this drilled section is around 0.14.

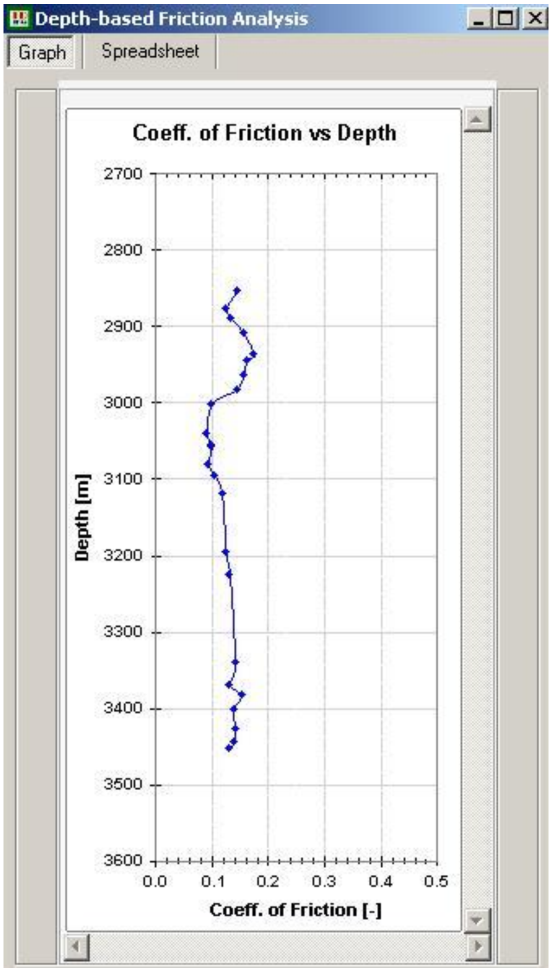


FIGURE 8 THE ESTIMATED FRICTION COEFFICIENT

Sensitivity Analysis on Drill String Element

The length of drill string element (ΔL in Eq. 1 and Eq.3 to Eq. 10) is one of the input parameters in the real-time torque and drag analysis. During drilling of the Western Canada well the inclination and azimuth were measured at different surveying points using a measurement while drilling (MWD) tool. When performing the data analysis for this well, IDAs downloads the survey points with inclination and azimuth versus measured depth from the data server. The length of the drill string between two survey points is taken as the individual element lengths used in this analysis, as discussed in the previous sections. Fig.9 represents the length of drill string (DS) element vs. depth based on the server provided survey measurement of the well. This figure shows the variation in DS element lengths with using the survey points for this horizontal well.

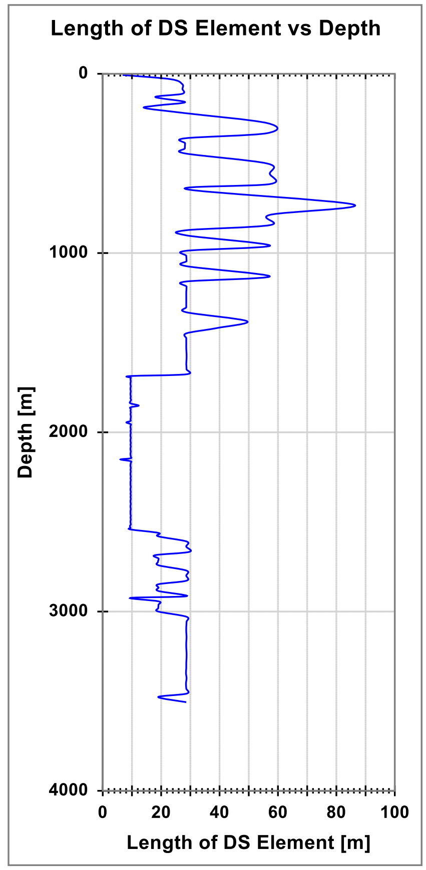


FIGURE 9 LENGTH OF DRILL STRING ELEMENT BASED ON SURVEY DATA

The kickoff point (KOP) of this well was at approximately 1700m as seen in Fig. 3. The precision of the wellbore trajectory is not complicated in the vertical section of the well (above KOP). Therefore the lengths between survey points varied above KOP as shown in Fig. 9. In this figure, the smaller lengths of the DS elements (around 10m) from approximately 1700m to 2500m represents the build up and beginning of horizontal section where precision of wellbore trajectory is very important.

IDAs can perform advanced investigations on the sensitivity of the wellbore friction model with different element lengths with constant length of the DS element, instead of variable DS element lengths (Fig. 9) for the same horizontal well. The constant lengths of drill string element considered are from 20m to 100m as shown in Fig. 10. The survey measurements of azimuth and inclination for user-defined constant element lengths are the interpolated values of the actual survey data provided by the data server.

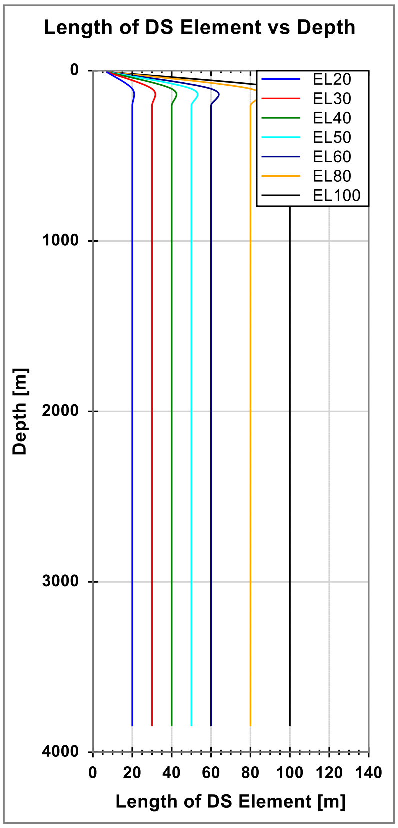


FIGURE 10 USER DEFINED LENGTH OF DRILL STRING ELEMENT

The sensitivity of this model is investigated by estimating the friction coefficient and DWOB using seven user-defined lengths as shown in Fig. 10. As an example, the drilled depth from 3369m to 3374m is used in this analysis with high frequency time based drilling data from the server. For this drilled depth, the estimated friction coefficient by considering element lengths based on actual survey measurement, is around 0.13 as shown in Fig. 8. The sensitivity of friction coefficient with constant element lengths for the drilled depth from 3369m to 3374m is shown in Fig. 11. According to this figure, coefficient of friction increases slightly with increase of constant length of drill string element.

The sensitivity of different user-defined element lengths on the estimated downhole WOB (DWOB) using IDAs is shown in Fig. 12 and the corresponding percentage of estimated DWOB over surface WOB (SWOB) for the same drilled depth is shown in Figure 13. The percentage of estimated DWOB over SWOB with constant element lengths ranges within values from 60% to 75%.

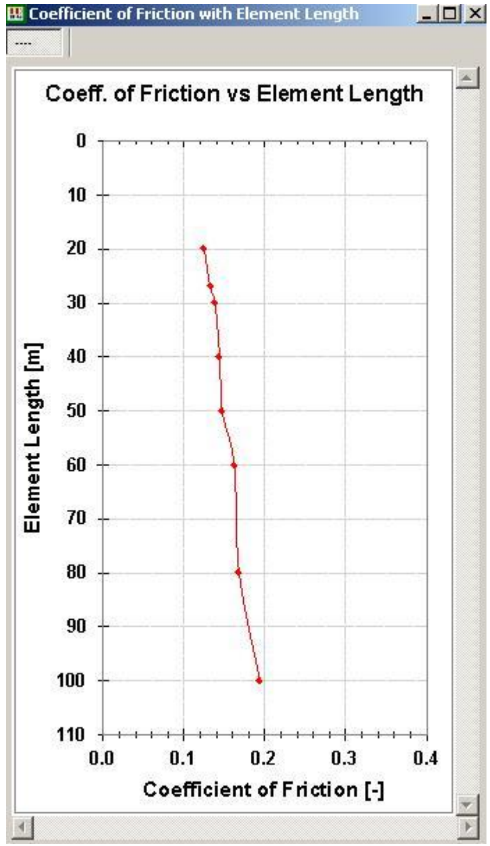


FIGURE 11 FRICTION COEFFICIENTS WITH CONSTANT ELEMENT LENGTHS

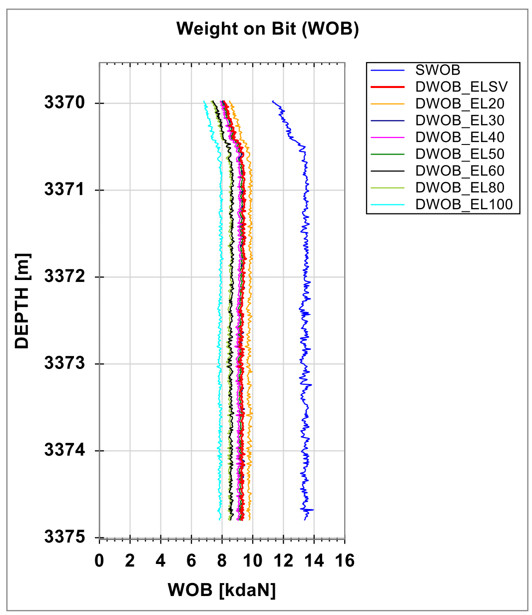


FIGURE 12 ESTIMATED DWOB WITH CONSTANT ELEMENT LENGTHS

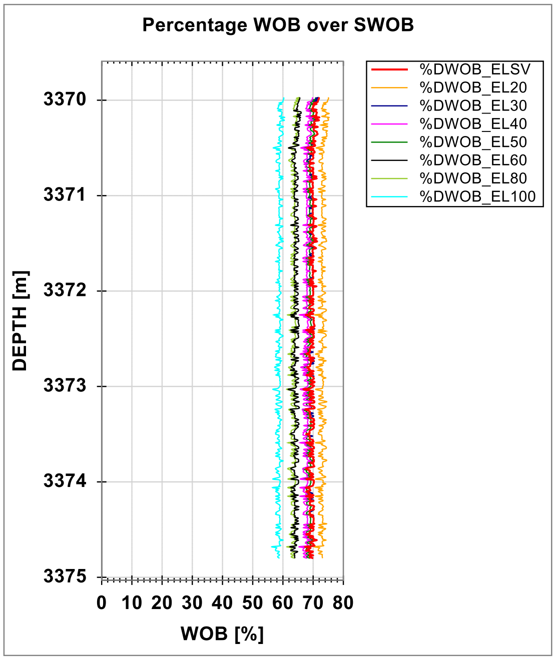


FIGURE 13 PERCENTAGE OF DWOB OVER SWOB WITH CONSTANT ELEMENT LENGTHS

Based on Fig. 11 to Fig. 13, the estimated friction coefficient and DWOB with element lengths of 30m and 40m have good agreement with the actual survey data having average DS element length of around 27m (based on Fig. 9) for this horizontal well section. Therefore, constant element lengths of 30m or 40m or 10m plus the average of actual survey data point frequency and corresponding interpolated/extrapolated measurements of inclination and azimuth can be used to estimate the friction coefficient and the downhole WOB effectively using this wellbore friction model IDAs in real-time.

CONCLUSIONS

The real time estimation of friction coefficient and downhole weight on bit during drilling of horizontal wells are investigated using newly developed and user-friendly real-time drilling engineering software, the Intelligent Drilling Advisory system (IDAs). A Web-based industry standard WITSML (Wellsite Information Transfer Standard Markup Language) is used to transfer drilling data from a remote WITSML server to client application, IDAs in office location.

The software uses a 3-dimensional wellbore friction model to estimate overall friction coefficient when the drill bit is off bottom and about to touch the bottom of the hole after each connection. Since different wellbore geometry has been considered in this model such as straight inclined and curved sections, this methodology can be applied for more complex well geometries.
The average friction coefficient estimated using IDAs is around 0.14. The estimated friction coefficient is then used to predict effective downhole WOB. The percentage of estimated downhole WOB over surface WOB ranges within 60% to 75%. The friction coefficient is calibrated before each drilling section for accurate prediction of downhole WOB in real-time. A good agreement between the estimated downhole WOB and the recorded WOB by the downhole measuring tool reveal verification of IDAs. More field trials will validate this analysis and the generate conclusions.

Based on the sensitivity analysis on the length of the drill string element the constant element lengths can be used in real-time analysis instead of variable lengths. This sensitivity analysis does not reflect or suggest on the possible improvement of wellbore trajectories or using more advanced drill pipe stiffness modeling problems. However, it verifies that the usage of constant length of drill string elements in the wellbore friction model for real-time analysis and the proper approximation of inclination and azimuth to predict friction coefficient and downhole WOB effectively during drilling of horizontal wells can be done.

The estimation of the overall friction coefficient helps detect possible tight hole or hole cleaning problems in extended reach wells. This may lead to a safer and more efficient drilling process in a real-time environment. The prediction of downhole WOB using IDAs may also help drillers apply more accurate WOB to improve rate of penetration. This engineering software can make engineers and drillers create a collaborative environment for smart decision-making and real-time drilling optimization of horizontal wells.

ACKNOWLEDGEMENT

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