Research

New Proposed Model for Torque and Drag Modeling

Seyed Ahmad Mirhaj[§*], Terje Tveitdal, Eirik Kaarstad

Address: Petroleum Engineering Department, University of Stavanger, 4036 Stavanger, Norway

Email: Seyed Ahmad Mirhaj - s.ahmad.mirhaj@uis.no, Terje Tveitdal - Terje.Tveitdal@halliburton.com, Eirik Kaarstad - eirik.karstad@uis.no

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[§]Corresponding author

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Abstract

Excessive drill string torque and drag is one of the major limitations of extended-reach and horizontal drilling. The torque and drag models are used in the planning phase and during the drilling of a well, as a tool used for monitoring developing hole problems. The models used throughout the industry today are mostly based on equations presented more than two decades ago, little work have been done to improve upon these.

The new 3D model presented by Aadnoy (2010) has some inaccuracy for the lower part of the string with low tension, since the side force due to the weight of the string is not accounted for. The Model Presented in this paper has improved the above-mentioned deficiency and results are more accurate with this model.

It has been also shown the importance of correcting for friction in the draw works sheaves to get realistic friction factors. A recently published model is used and work has been done to improve this model further.

Introduction

Excessive drill string torque and drag is one of the major limitations of extended-reach and horizontal drilling. The torque and drag models used throughout the industry today are mostly based on the equations presented by Johancsik (1984), little work have been done to improve upon these. This thesis presents a field application of a new friction model for petroleum wells. The model is relatively simple and is applicable for any 3-dimensional wellbore trajectory. The friction in the entire well is modelled by two equations, one for straight and one for curved wellbores. Like most friction models it assume that the drill string can be modelled as a soft string like a cable or chain that has no bending stiffness. In the upper part of a well where weight of a string segment is negligible compared to tension load, simplified equations can be used. Friction is modelled in terms of the 3D dogleg. A torque and drag model may incorporate corrections for hydrodynamic viscous drag force, wellbore contact surface, density corrections due to filling of pipe during tripping in and draw works sheave friction.

Critique of the new analytical 3D model

The new model has very simple formulation, which allows for quick computation time. When the tension is so high that the side force due to tension is a lot greater than the side force due to the weight of the pipe, the new 3D model works great. When tension is high it matches field data as shown by Mirhaj (2010), however, he also showed that the model gives an under prediction of friction in the lowest part of the string which has low tension. The reason for this under prediction can be seen by examining equation for the new model:

$$F_2 = F_1 e^{\pm\mu|\theta_2-\theta_1|} + w\Delta TVD \tag{1}$$

We see that if there is a horizontal side bend, the equation will be reduced to:

$$F_2 = F_1 e^{\pm\mu(\theta_2-\theta_1)} \tag{22}$$

When tension is low, the position of the string in the wellbore will be given by the sum of the gravity vector and the side force vector due to the bend. But the side force due to the weight of the pipe itself is ignored. In a horizontal side bend as shown in **Fig. 1** the pipe in the hole will lie on one sidewall if the tension is high. On the other hand, if there is no tension, the pipe will be gravity dominated and lies on the low side of the hole. The problem of under prediction of drag in a horizontal section with low tension was solved by Mirhaj (2010), he introduced a new tension criteria. In the criteria drag could be calculated by straight segment equation when the tension is low. With the new criteria more drag was predicted in the part of the string with low tension. But then the string is assumed to be on the low side when tension is low, and on the side of the wall when tension is above the critical limit. But in reality the string will be positioned somewhere in between these two extremes.

So clearly the new model has some inaccuracies for the lowest part of the string where tension is low. It is worth noting that the side force effect of the string weight will be reduced the higher the pipe lies on the borehole wall. When a string is in the 3 or 9 o'clock position, the effect of the string weight on side force will be zero. This is shown in **Fig. 2**, where the normal force due to gravity is greatest for the pipe on the low side.

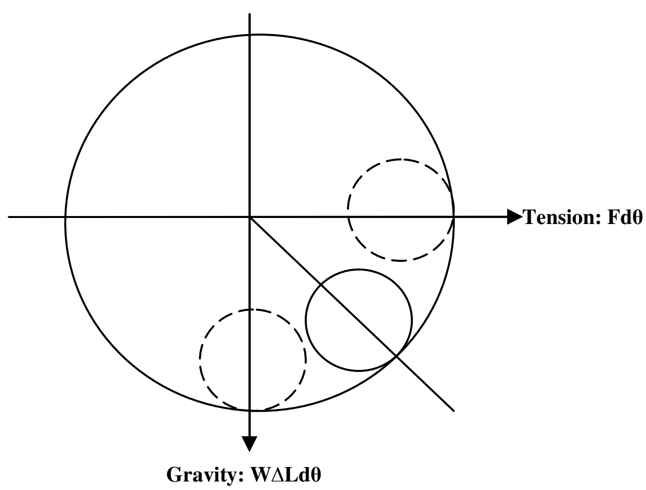

Figure 1: String position in a borehole.

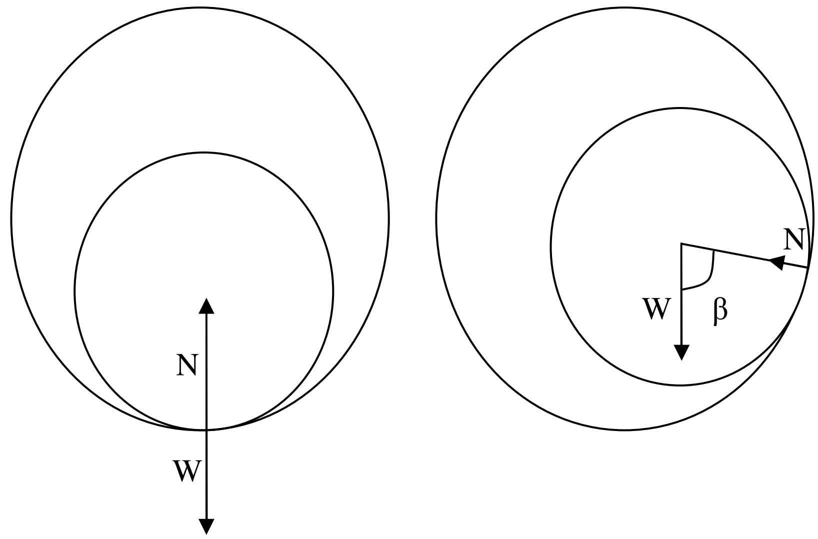

Figure 2: Forces due to gravity on horizontal pipe

New Proposed Model

To improve upon the deficiency when the tension is low we try to have a different approach to the problem. We consider an element of pipe and decompose the tension vector from previous segment into its horizontal and vertical components by using trigonometry. Then use the exact analytical equations for a horizontal side bend and the new 3D model (Aadnoy et. al., 2009) is used in 2D for the vertical bend. By 2D we mean that for the vertical bend, only the change in inclination is considered. As it can be seen from **Fig. 3** side C can be decomposed into its horizontal component b, and its vertical component a. Note that the lines in the triangle are curved as if it is on the surface of a sphere.

Remembering that the most common well path model the "minimum curvature method" assumes the well path to be wrapped around the surface of a sphere, which is the largest sphere possible that will fit between the survey points. In other words, the sphere has "minimum curvature". This is shown in **Fig. 4**, where the largest sphere g, fits in between survey station A and B.

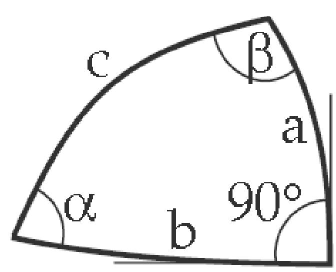

Figure 3: A triangle on a sphere

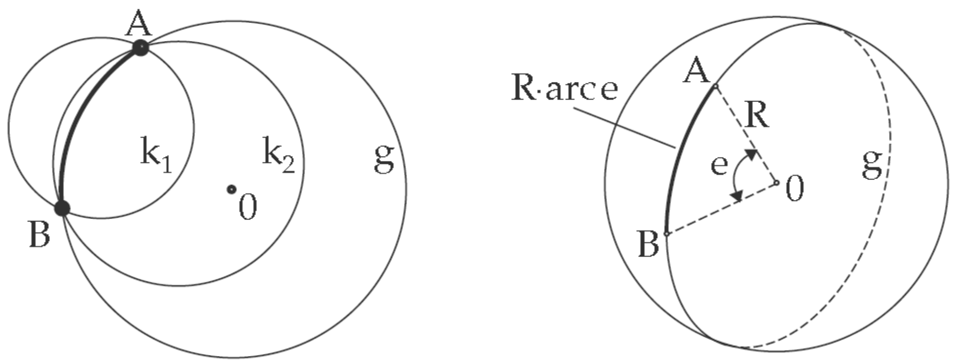

Figure 4: Minimum curvature method

Since the radius of the sphere is a lot larger than the length between two survey stations, we may simplify slightly and use the Pythagorean theorem, instead of using more involved spherical trigonometry.

The horizontal component can be found by:

$$F_{\alpha,i} = F_{2,i-1} \cos\left(arctan\left(\frac{\Delta\,\varphi}{\Delta\,\alpha}\right)\right) \tag{3}$$

The vertical component can be found by:

$$F_{\varphi,i} = F_{2,i-1} \sin\left(\arctan\left(\frac{\Delta\,\varphi}{\Delta\,\alpha}\right)\right) \tag{4}$$

Then both the vertical and horizontal drag forces can be calculated individually. The vertical component on top of the element $F_{\varphi,2}$, and the horizontal component on top of the element $F_{\alpha,2}$. The net force on top of the segment F_2 is then calculated by re-combining using Pythagorean theorem and adding a term for the weight of the pipe:

$$F_2 = \sqrt{{F_{\varphi,2}}^2 + {F_{\alpha,2}}^2} + w\Delta TVD \tag{5}$$

Where true vertical depth of a segment may be found with minimum curvature method, or by approximation by:

$$\Delta TVD = R(\sin\varphi_2 - \sin\varphi_1)$$

Or alternatively, with radius of curvature method:

$$\Delta TVD = \Delta L\left(\frac{\sin\varphi_2 - \sin\varphi_2}{\varphi_2 - \varphi_1}\right)$$

Likewise this process will be repeated for the next upper element. The flowchart in **Fig. 5** shows how the model selects which equations that should be used.

This method of decomposing the force into its horizontal and its vertical components based solely on the change in inclination and azimuth is not an exact method. Some errors will be introduced when decomposing and recombining the forces. Trying to model a whole well by this method can be done, but the error introduced will be greater. There is no reason for doing that because when tension is high, the effect of pipe weight can be ignored, and the new Aadnoy 3D model works well then. So this method is proposed to be used only where the side force due to the weight of the string is not to be ignored, that is when the string has low tension. This method is a better solution, than assuming that straight segment equations can be used.

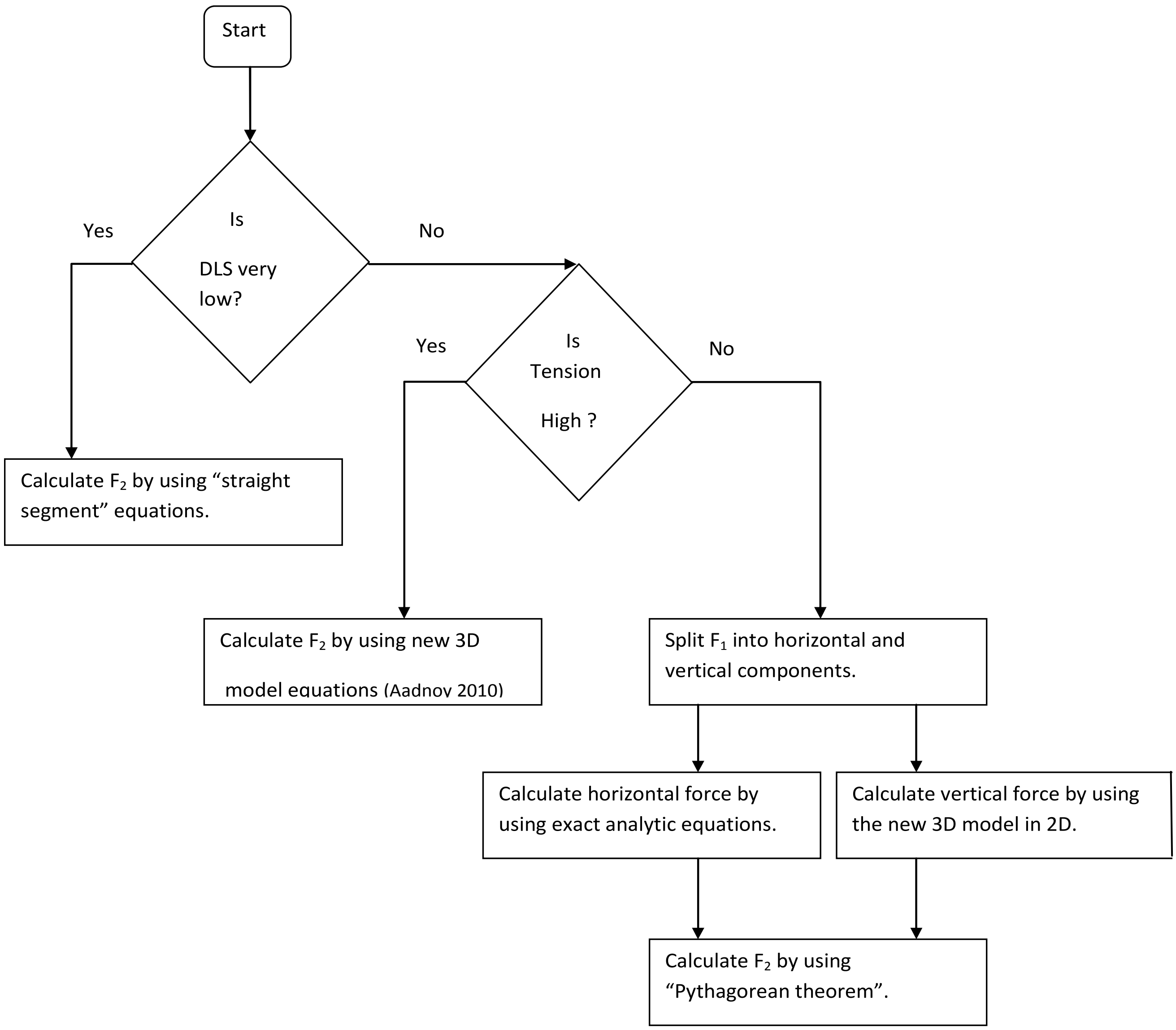

Figure 5: Flow diagram showing how to calculate tension on top of a segment

The approach to find the critical tension limit in above flowchart is to calculate ratio between the side force due the weight of the pipe, and side force due to tension and curvature. By plotting this ratio we can set the tension limit to the tension in the string where the ratio starts to increase. That is where the side force due to tension is starting to be dominating over side force due to the weight of the string, for a specific segment. This ratio can be found by:

$$R = \frac{w\Delta L \sin\varphi}{F\theta} \qquad (6)$$

Field Case to test the model out:

The well has been selected for the case study is a horizontal well drilled in the North sea. It was drilled from a Jack up rig to TD at 6015 m MD. A 13 5/8" casing was set to 1730 m MD. And a 10" liner was set from 1701m MD to 4501 m MD. A well schematic with the 8.5" drilling assembly is shown in **Fig. 6**.

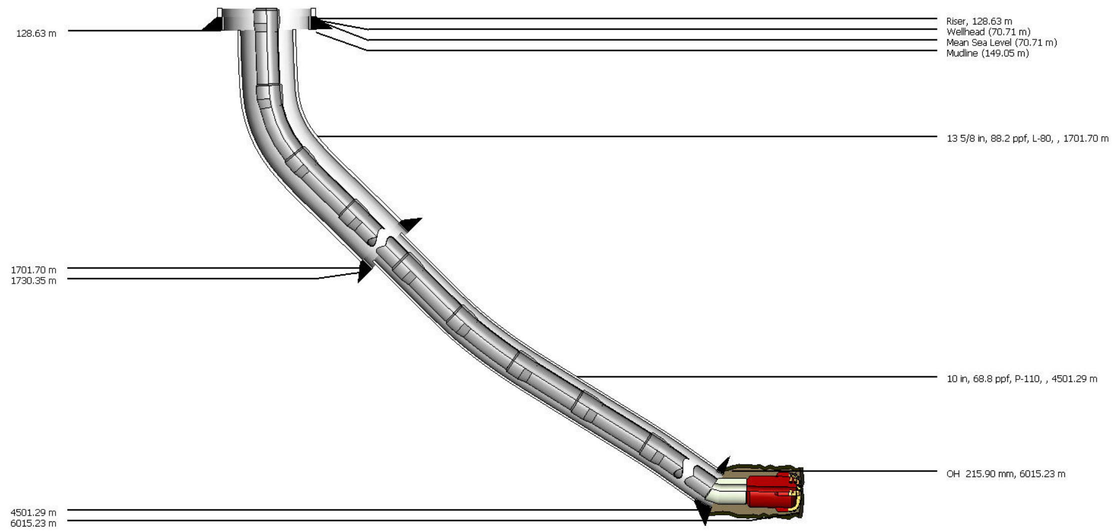

Figure 6: Field case well schematic

This well builds angle three times:

1. The first KOP 600 m.
2. The second at 2000 m TVD.
3. Final build to horizontal at 3200 m TVD.

The dogleg severity in this well is not very large, with a maximum of 4 deg/30m at 4600 m MD.
This example well was drilled with Halliburton ADT service which used Landmark's Wellplan software for simulating torque and drag in order to monitor the hole conditions by comparing actual field measured hookload and torque with the model. Very consistent hookload data was measured for hoisting, lowering and static weight, as well as free rotating torque. These measurements were done at every stand before a new connection was made. The measured hookloads for lowering, static and hoisting are plotted and the model in wellplan was first tuned to match the static weight, and then to hoisting and lowering weights. A combined plot shows the measured weight and the wellplan model for both the 12.25" section and the 8.5" section in **Fig. 7** The sudden jump at 4500 m is due to a lighter BHA was used to drill the lowest section. This is due to 8" MWD tools were used in the 12.25" section, while in the 8.5" section the smaller 6 ¾" MWD tools were used.

The drill string and borehole used in all simulations are the same as the one that was used in Wellplan.

Sheave friction

It is possible to tune the models so that we get a good match between field measured data for hoisting, lowering and static weight. However, the method used to tune the model can rise to questions. Firstly the "static weight" off bottom is not dependent on friction factor, but only on unit weight of string, mud weight and vertical depth. So if measured static weight does not match the model, either wrong string weight has been entered to the model or the hookload sensor is out of calibration. The modelled static weight has to be tuned to match field data either by correcting the unit pipe weight or by calibrating the measured hookload. Secondly the hoisting and lowering weights are measured with moving sheaves in the crown and travelling block and are therefore affected by sheave friction. This means that the measured weight are actually a bit lower for hoisting and higher for lowering than it is in reality. Corrections for sheave friction may be applied either to the model or to actual measured data. In **Fig. 8**, Wellplan is used for modelling of drilling in the 8.5" section. The model is matched to actual values but there is no correction for sheave friction. The friction factor to match is very low, 0.16 for lowering and 0.14 for hoisting. We might say that the sheave friction is then included in "fudge" of the friction factor. This might seem unrealistically low, but this is actually how the company who drilled this well tuned in their model.

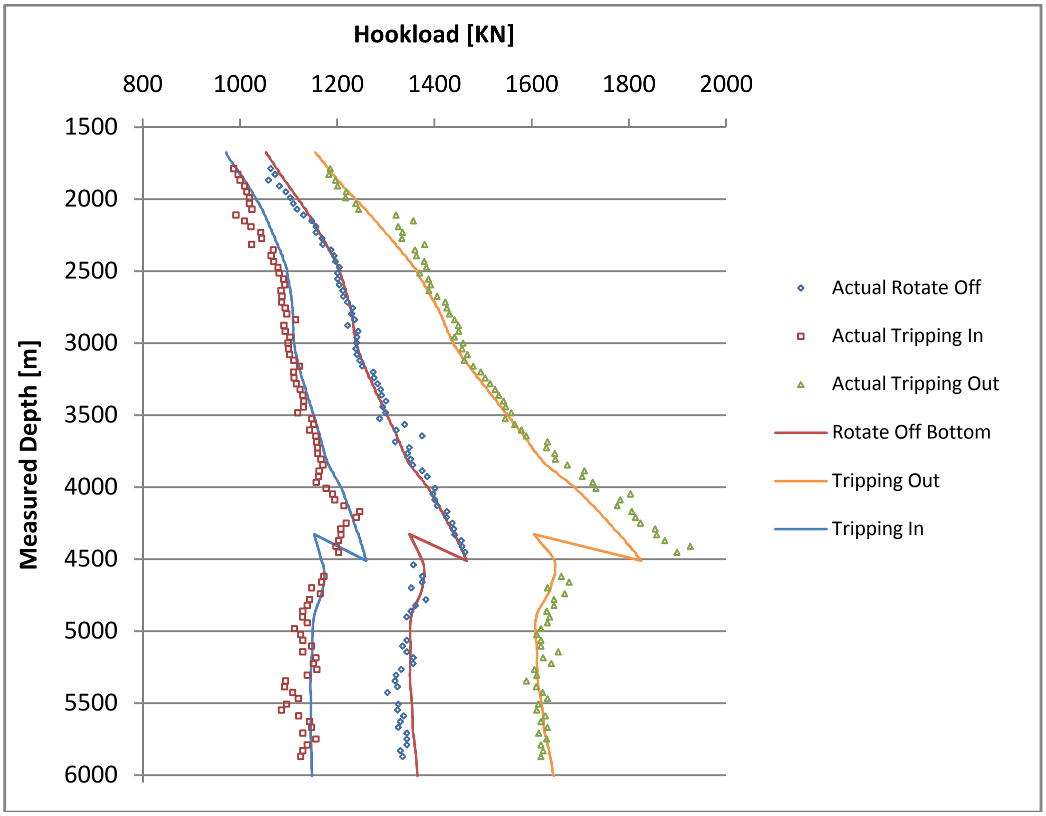

Figure 7: From Wellplan, drilling 12.25" and 8.5"

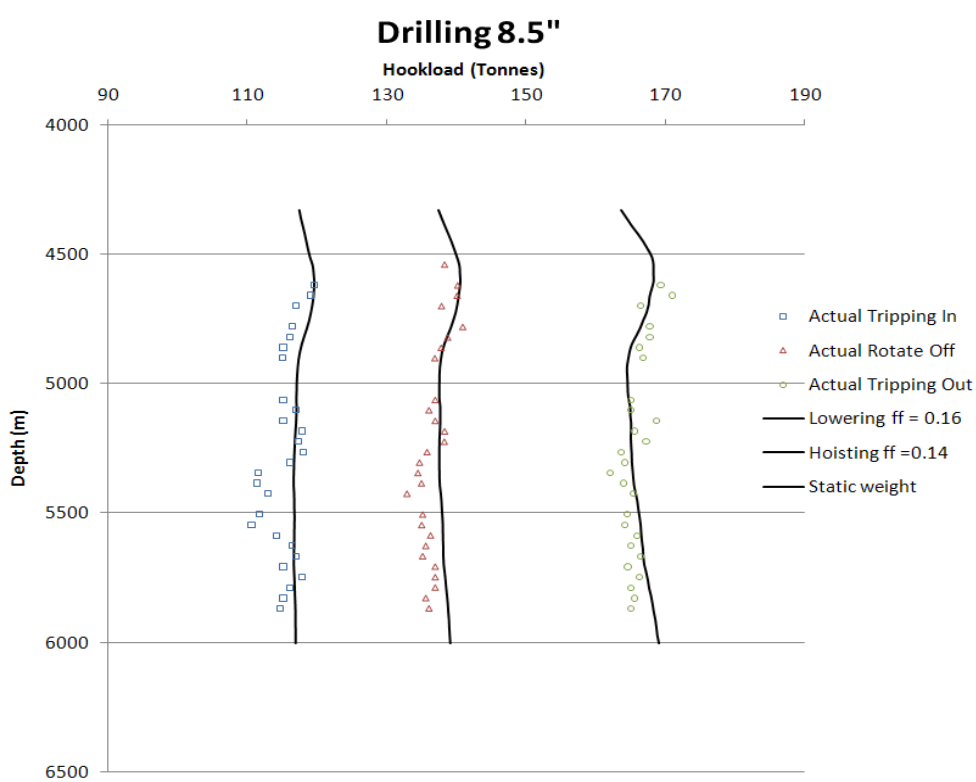

Figure 8: Matching actual data with no sheave friction correction.

This way of tuning in the drag model could without doubt been improved. But it comes down to what the model is used for and the quality of available data. In the case of this well the main purpose was to monitor hole condition for signs of trouble like cutting accumulations and hole cleaning. Experience with many wells told them that they would only need to do remedial action whenever actual hookload deviated by more than 9 Tons from the model. For this use the numeric value of the hookload is rather uninteresting, it is rather the trend and the sudden deviations from the trend that is the most interesting.

If we apply sheave friction correction to the model, the result is shown in **Fig. 9**. In this case effect is that the curves are shifted by about 20 Tons. More accurate data would need to be available to do an accurate calibration of the sheave efficiency, so in this case a typical (Luke 1993) sheave efficiency of 98% was used.

If we now tune the friction factor, we can match the actual data by a higher and more realistic friction factor. In **Fig. 10** the actual data are matched by a friction factor of 0.28 for hoisting and 0.21 for lowering. This shows that the effect of sheave friction is something that we need to consider. Even though sheave efficiency is rather difficult to determine accurately.

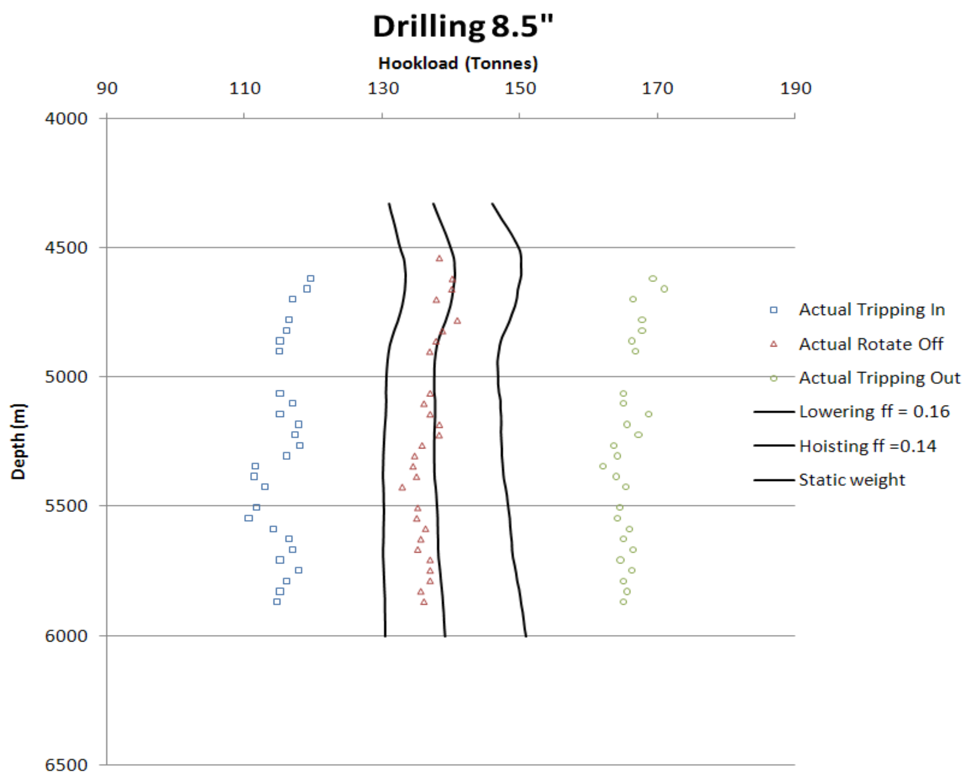

Figure 9: Sheave friction correction applied to the model.

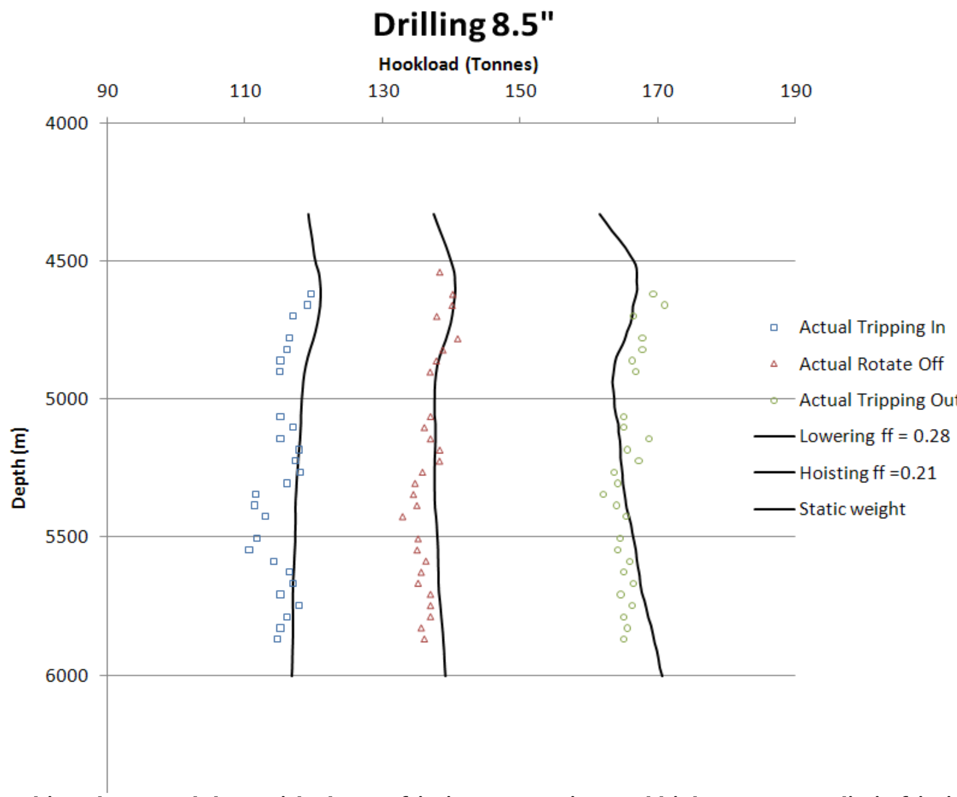

Figure 10: Matching the actual data with sheave friction correction and higher more realistic friction factors

It was tested to see how the model for low tension would perform. The same field case well was used, this time it was tested against Aadnoy's new 3D model for hoisting and lowering. This test was done with the standard straight/curved criteria for the 3D model, with a curvature limit of 0.03 radians and a tension limit of 700. This tension limit was found by calculating the ratio between side force due to weight of the pipe and side force due to the tension and curvature, by using equation (6). By examining **Fig. 11**, we see that the side force ratio for hoisting is below 2 for the lower part of the string and then increases rapidly further up. This is where we should set the tension limit. A tension in the string of 700 KN is found where the ratio is 3 for both lowering and hoisting. Higher up the string the tension ratio is so much higher that it side force due to pipe weight is negligible as compared to the side force due to tension and curvature.

Fig. 12 shows the tension in the string for hoisting and lowering with bit close to TD. The red dots show segments where the new proposed model is used, green dots shows segments where straight line equations are used and blue dots shows segments where the new 3D model is used. We see that the curves for hoisting and lowering with new model and the 3D model are overlapping and the results are very similar, except that the new model gives slightly higher hookload for hoisting and slightly less hookload for lowering. This is as expected from theory since the new model includes drag due to curvature and account for the position of the pipes position on the wellbore wall while the other model assumes straight line equations.

For POOH and RIH with the model presented in this paper, as shown in **Fig. 13** and **Fig. 14**, We see that the calculated result is very similar for both models, except that the new model predicts slightly less hookload for lowering while RIH, and predicts a slightly higher hookload for hoisting while POOH.

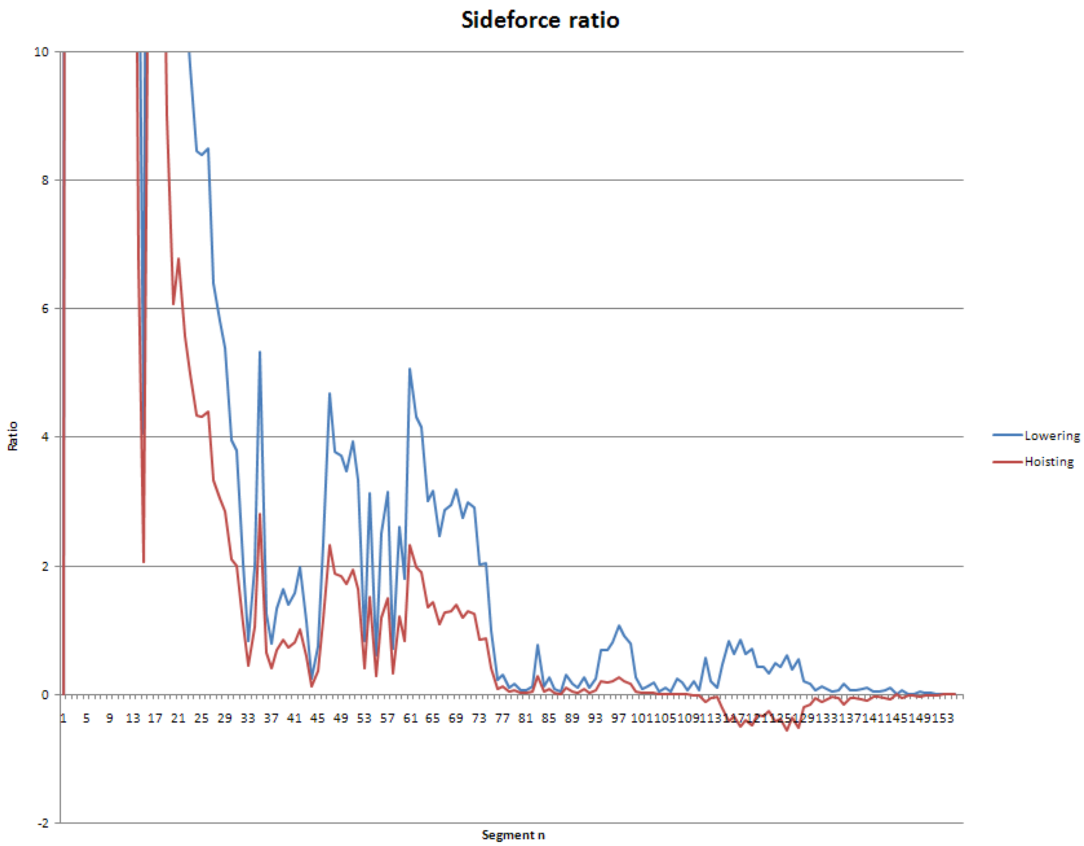

Figure 11: Side force ratio.

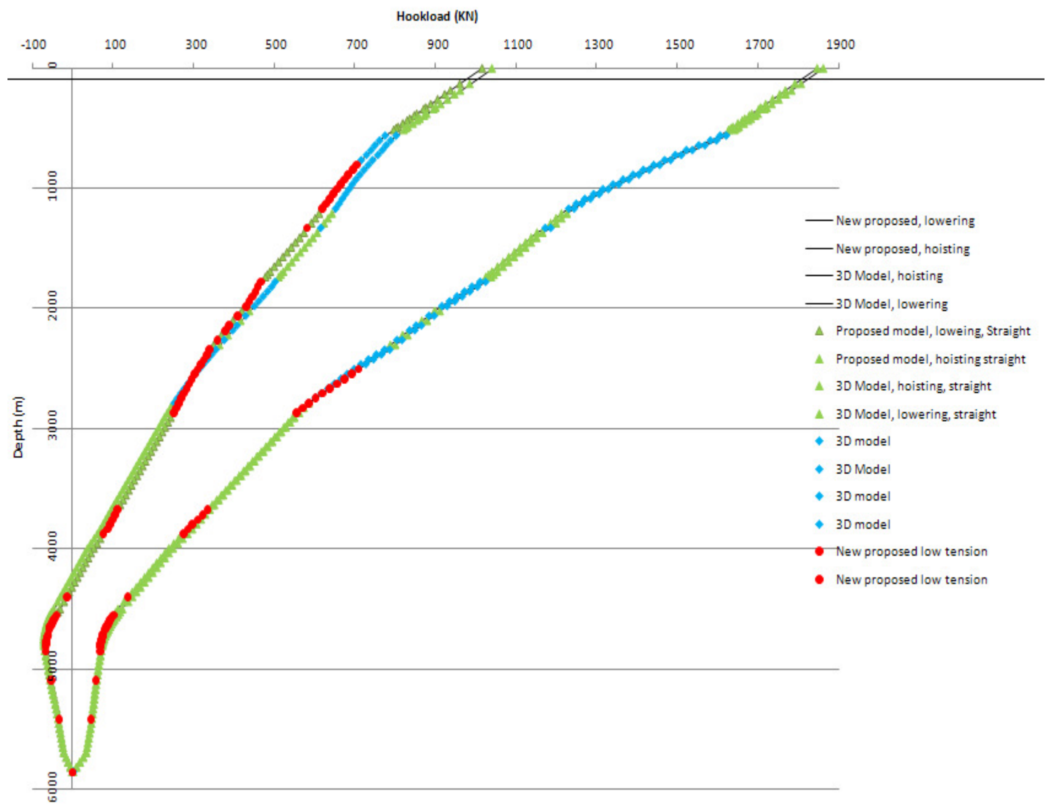

Figure 12: Hoisting and lowering with the new model

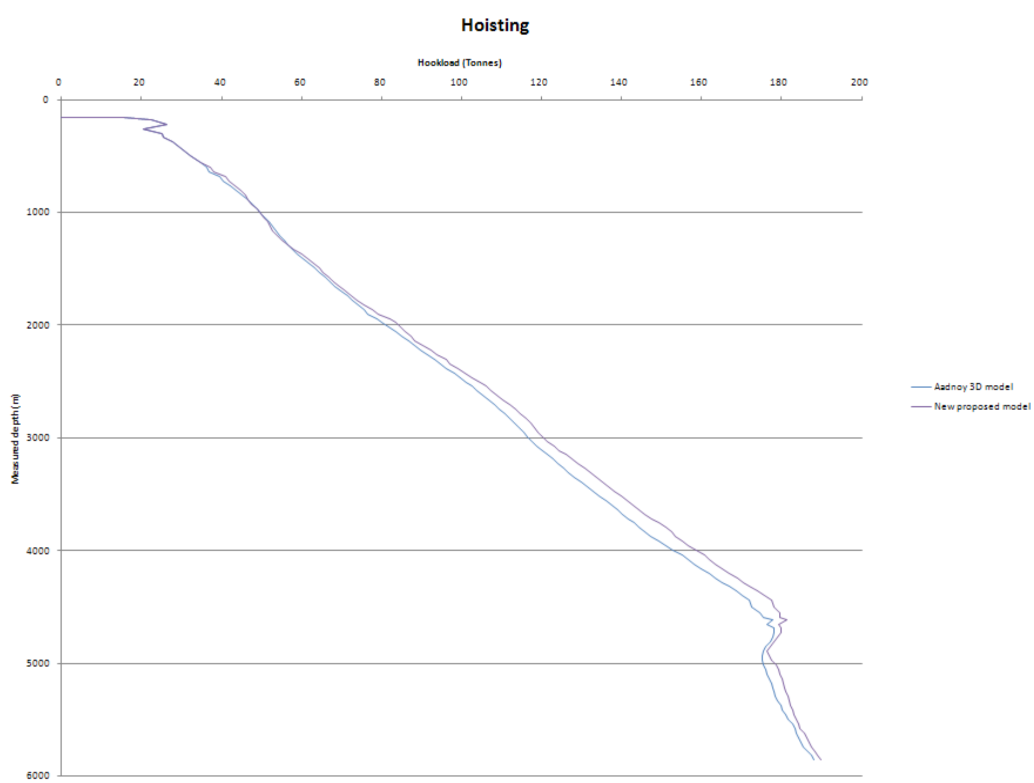

Figure 13: POOH with the new model.

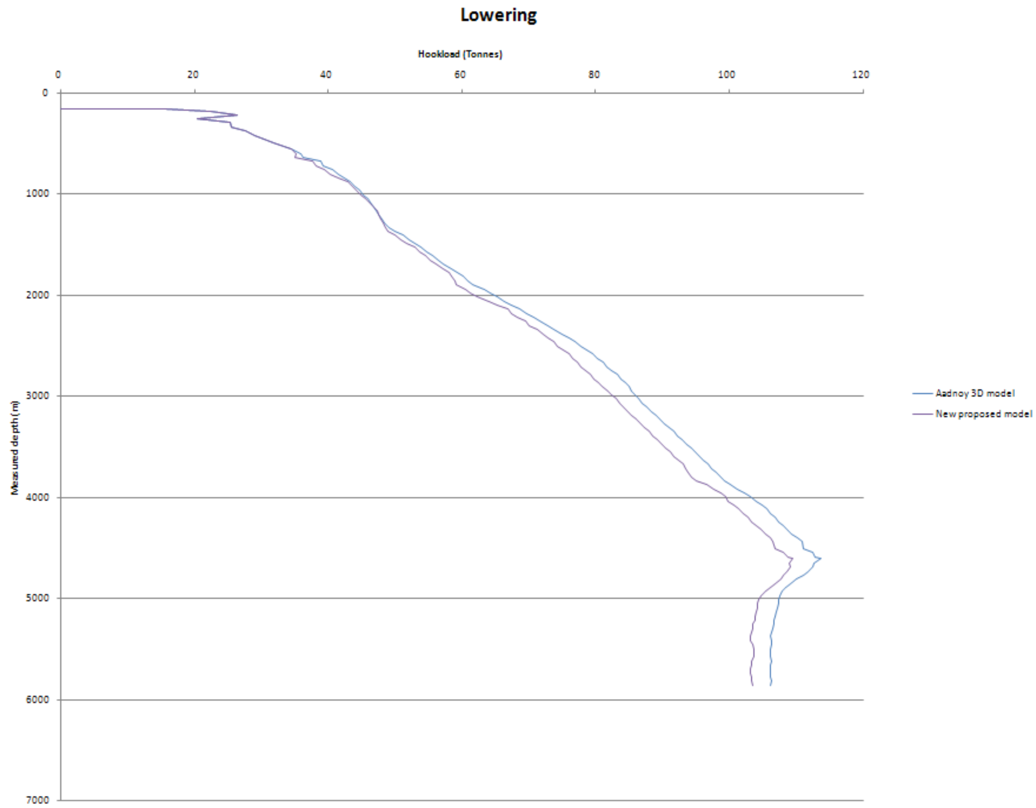

Figure 14: RIH with the new model

Conclusion

The following conclusion has been taken from this paper:

- The new 3D model has some inaccuracy for the lower part of the string with low tension, since the side force due to the weight of the string is not accounted for. A new approach to this problem has been taken, and a new model is proposed and presented for the first time. This proposed model for the lowest part of the string, accounts for side force due to weight of the string, the position of the string in the borehole and the curvature in 3D. From the specific field case study, the model presented here predicts slightly more drag than the previously used model.
- The friction factor is a lumped parameter which is dependent on many factors, not just true mechanical friction. Friction in the draw works sheaves affects the hoisting and lowering weights. It has been shown in the thesis how this effect can be corrected for. Some of the "fudge" in the friction factor can then be removed and a more realistic friction factor can be obtained.

Nomenclature

F = Drag force
$F_{\varphi,2}$ = Tensile/compressive force at top of segment in vertical plane
$F_{\alpha,2}$ = Tensile/compressive force at top of segment in horizontal plane
$F_{2,i-1}$ = Tensile/compressive force at top of pipe segment
R = Radius of curvature

w = Pipe weight
θ = Dogleg angle
φ = Inclination angle
ΔL = Length of pipe elements
ΔTVD = Change in True Vertical Depth
$\Delta\varphi$ = Change in inclination angle
$\Delta\alpha$ = Change in wellbore Azimuth

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Appendix A

A.1 Forces in a horizontal side bend

Aadnoy and Andersen (2001) derived exact analytical equations for torque and drag in drop-off, build-up and side-bend geometries. In flowchart, **Fig. 5,** in the case that the tensile force is below the limit based on equation (6), the force will be split into horizontal and vertical components. The horizontal component will be calculated from exact analytical equations by Aadnoy and Anderson (2001). The corresponding equations have been listed in the table below. These equations are assuming that the weight of pipe in the side bend is also contributing to total side force.

A.2 The new 3D model for curved segments only

In the 3D model (Aadnoy et. al. 2010) for curved segments an assumption is made that the string is weightless, to find an expression for effect of tension, and then adds the weight of the string to the final result. In flowchart, **Fig. 5,** in the case that tensile force is above the limit based on equation (6) this 3D model will be used. Moreover in the same flowchart in the case that tensile force is below the limit of equation (6) and the force is being split into vertical and horizontal components, 3D model in 2D is used to calculate the vertical component of tensile force. The corresponding equations of 3D model have been listed in the table below.

Lowering	$F_2 = \frac{1}{2}\left[\left(F_1 + \sqrt{F_1^2 + (wR)^2}\right)e^{\mu(\alpha_2-\alpha_1)} - \frac{(wR)^2}{\left(F_1 + \sqrt{F_1^2 + (wR)^2}\right)e^{\mu(\alpha_2-\alpha_1)}}\right]$
Hoisting	$F_2 = \frac{1}{2}\left[\left(F_1 + \sqrt{F_1^2 + (wR)^2}\right)e^{\mu(\alpha_2-\alpha_1)} - \frac{(wR)^2 e^{\mu(\alpha_2-\alpha_1)}}{\left(F_1 + \sqrt{F_1^2 + (wR)^2}\right)}\right]$
Torque	$T_2 = T_1 + \mu r\lvert\alpha_2 - \alpha_1\rvert\sqrt{F_1^2 + (wR)^2}$

Table A-1: Forces in a side bend

Hoisting and Lowering curved	$F_2 = F_1 e^{\pm\mu\lvert\theta_2-\theta_1\rvert} + w\Delta TVD$
Torque curved	$T_2 = T_1 + \mu r F_1\lvert\theta_2 - \theta_1\rvert$

Table A-2: Summary of the new 3D model