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Wellbore Friction Analysis to Detect Onset of Drillstring Sticking during Extended Reach Well Drilling: Case Study

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Abstract

Wellbore friction modeling is considered as an important assessment to aid real-time drilling analysis and predict drilling troubles such as tight holes, poor hole conditions, onset of pipe sticking etc. The torque and drag are typically the limiting factors facing the drilling industry to go beyond a certain measured depth in extended reach drilling. In extended reach drilling, surface measurement of weight on the bit and torque differ from downhole measurement due to the friction between the drill string and the wellbore. This friction force can be used to estimate an overall friction coefficient. The overall friction coefficient value versus measured depth while drilling can be used as an indicator during different drilling operations.

In this paper, for wellbore friction analysis, a newly-developed analytical model was used to estimate the friction coefficient versus measured depth. A field case is drawn from a deviated well drilled in western Canada where the drillstring got stuck during drilling operations. The time-based field data were analyzed in detail to find onset of drill string sticking from the recorded data while tripping. Also, the study provided an opportunity to examine the validity of the new friction model using a field case.

Wellbore Friction Modeling

For wellbore friction analysis, consider an element of the drillstring in the wellbore which is filled by drilling fluid. The forces acting on the pipe element are buoyed weight, axial tension, friction force and normal force, $F_{N,}$ perpendicular to the contact surface of the wellbore. Calculation of the normal force is the first step in calculating the friction force for an element of the drillstring. The friction force is defined as an acting force against pipe movement which is equal to friction coefficient multiplied by the normal force as in equation 1.

$$FF = \mu \times F_N \quad (1)$$

In straight inclined and horizontal sections, the normal force is equal to the normal weight of the element and there is no other contribution. But, for a curved section such as build-up, drop-off, side bends and/or a combination of them, the normal force [] mostly depends on the tension at the bottom end of pipe element and less on the weight of the element [Aadnoy, B.S. and Andersen, K. 2001]. The following general equation defines the tension at the top of each element.

$$F_{top} = F_{bottom} + Static\ \ Weight\ \pm \mu \times F_N \quad (2)$$

"top" and "bottom" represent the location of the drillstring element where the tension force applies.

The weight and friction force of each element should be calculated and added up from bottom to the surface. In equation 2, the plus and minus signs are for pipe movement either up or down, respectively. For a drilling operation, the weight on [] bit should be deducted from the right hand side. The weight on bit can affect the value of the friction force in the curved section which should be considered during analysis [Fazaelizadeh et. al. 2010].

For a straight inclined element, the normal force is weight dominated and is not dependent on axial tension at the bottom of element. The coulomb friction model can be used as shown in equation 3.

$$F_{top} = F_{bottom} + \beta \times w \times \cos\alpha \pm \mu \times \beta \times w \times \sin\alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Aadnoy et. al. (2010) did the following derivation for a curved section. They assumed that the pipe was weightless when the friction force was computed, but added the weight at the end of the bend. They also used the concept of dogleg angle, θ, in their derivation which depends on both the wellbore inclination and [] azimuth. Because the pipe will contact either the high side or the low side of the wellbore, its contact surface is given by the dogleg plane. The dogleg is the absolute change of direction which can be determined by the following equations:

$$\cos\theta = \sin\alpha_{top} \sin\alpha_{bottom} \cos(\phi_{top} - \phi_{bottom}) + \cos\alpha_{top} \cos\alpha_{bottom} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

For build-up, drop-off, side bends or combination of these, the axial force becomes:

$$F_{top} = \beta w \Delta L \left\{ \frac{\sin\alpha_{top} - \sin\alpha_{bottom}}{\alpha_{top} - \alpha_{bottom}} \right\} + F_{bottom} \times e^{\pm\mu|\theta|} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Overall friction for any wellbore shape can be computed by dividing the well into straight and curved elements. The forces are then summed up starting from the bottom of the well.

Buoyancy Effect

The principle of Archimedes law is used in the buoyancy calculations. The principle says, when a body is submerged into a fluid the buoyancy force is equal to the weight of the displaced fluid. The drillstring tension in a wellbore which is filled with a drilling fluid is the unit [] weight of pipe w multiplying by the buoyancy factor β. The equation 6 is valid for either a vertical and deviated borehole if the inside and outside of the pipe are submerged into the same fluid.

$$\beta = 1 - \frac{\rho_{mud}}{\rho_{pipe}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Equation 6 gives an estimation of the buoyancy factor when the drilling fluids are incompressible and the effect of temperature and the cutting concentration is ignored. This equation can be used for all overbalanced drilling operations unless tripping in which is discussed in the next paragraph.

If there is a density difference between the inside of the string and the annulus like during cementing and tripping in operations the following equation should be used [Aadnoy, B.S. and Andersen, K. 2006].

$$\beta = 1 - \frac{\rho_o d_o^2 - \rho_i d_i^2}{\rho_{pipe}\left(d_o^2 - d_i^2\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where subscript "*o*" and "*i*" refers to the outside and the inside of the drillstring.

Equation 7 can calculate the buoyancy factor locally for each element. In tripping in operations, the annulus is completely full while drilling fluid level varies inside drillstring. The reason why the drillstring is not or only partially filled with fluid is, [] the rig crew typically does not fill the drillstring after every connection. By considering the collapse pressure of the drillstring and risk of fluid loss and flow, the rig crew will typically schedule to fill the drillstring after running a few hundreds meters of pipe. This means the drillstring will be partially filled for a period of time and then will be completely full after filling the inside of the drillstring. When the drillstring is full of mud, the equation 7 will turn to equation 6. When the drillstring is partially full and a portion of the drillstring has been filled with drilling fluid, the equation 7 will be used for buoyancy factor calculation of each element. This approach was integrated into the tripping in friction analysis in the case study presented herein.

Contact Surface Effect

The correction factor, C_s, represents an effect of the contact surface between the pipe and the wellbore due to larger curvature surface contact. To include the contact surface effect in the friction equations, it should be multiplied by friction coefficient. In the case of the drillstring being in contract with the wellbore, the friction force can be written as:

$$FF = C_S \times \mu \times F_N \qquad (8)$$

This correction factor values that vary between 1 and $\frac{4}{\pi}$ [] depend on the contact surface angle, γ, which varies between 0° and 90°. Contact surface angle γ_i is mainly dependent on the wellbore and drillstring outer diameters.

$$Cs_i = \frac{2}{\pi}\gamma_i\left(\frac{4}{\pi}-1\right)+1 \qquad (9)$$

Maidla and Wojtanowicz (1987) discussed the contact surface correction factor and how to use it in friction force calculations. In some well portions the hole size is [] slightly smaller than usual due to wellbore swelling, thick mud cake, cutting accumulation etc. These possible reductions in hole size could show higher friction value when BHA passes through them. When this situation happens, it could be required to do some remedial action such as drillstring rotation to ream the tight area. The friction force could increase differently depends on the degree of severity of those tight spots.

Results and Discussion

A well drilled in western Canada is used to illustrate the friction analysis. The overall well geometry is shown in [] Figure 1. The well depth was 3251m when the drillstring got stuck during drilling operations. The well profile included a kick off point at 800m and the heavier build section initiated at 2287m. The well reached an angle of 30 degree inclination at approximately 2700m and drilled to a total depth of 3231m holding the inclination of 30 degrees. At this depth the drill string was tripped out for the purpose of replacing the Measurement While Drilling (MWD) tool. The drilling process was continued after the tripping in procedure for only 20 m. At the depth of 3251 m the drill string got stuck. The drillstring configuration was not changed from 2200 m to 3251m. The BHA had a length of 290 m from the bit. The BHA has a large effect on the value of friction force during tripping in and out. For example, any interval in the wellbore which has a smaller diameter due to formation swelling applies a higher friction force against the BHA movement.

Another important factor which should be considered during friction analysis is the buoyancy factor which changed during different drilling operations. In Figure 2, the Buoyancy factors of the three operational modes have been shown. During the drilling process, the buoyancy factor maintained a constant value until the depth of 2485 m when the mud weight was increased as much as 300 kg/m^3 to prevent gas inflow. This increase led to a decline in the Buoyancy factor. The tripping out process exhibits a nearly constant buoyancy factor since the mud weight has been kept constant and the level of mud in the annulus dropped a little.

The Buoyancy factor during the tripping in process shows a gradual decrease due to increasing [] length of the non filled pipe. Since the drill string is filled periodically, some jumps in buoyancy trends can be observed. The increase in the level of drilling fluid in the drillstring leads to an increase in the buoyancy factor.

The above mentioned increase in mud weight due to gas influx resulted in a down hole pressure rise as shown in Figure 3. This increase in the mud weight enhances the differential pressure between the drill string and the formation and applies additional force on the pipe. Although the increase in mud weight decreases the normal force on the drillstring due to [] change in the Buoyancy factor, the excess differential pressure has an effect of larger magnitude which in turn, increases the frictional force. For example, in any pipe sticking problem, the first remedial action will be reduction in mud weight to decrease the differential pressure between drillstring and the formation. In most of the cases, this reduction may help to release the drillstring from the stuck point.

Figure 4 compares the hook load recorded during tripping in and out of the well. These data were used to do the friction analysis for this case. The periodical shifts in hook load values during tripping in are due to the increased Buoyancy factor as the fluid fills the drill string. These jumps are not observed during the tripping out process because the Buoyancy factor is almost constant. A deviation from the hook load trend may be seen as the build-up section begins at the depth of 2287 m due to the friction force increase in the build-up section.

Figure 5 presents the frictional force during the tripping out process. The friction force is calculated from the difference between the static weight of drillstring and the hookload value. The friction in the curved section is tension dominated which shows rapid increase in the value of the friction force. As the top of the bottom hole assembly reached the buildup section, an increase in the frictional force occurred around 2900m. As the BHA passes through the buildup section, the frictional force declines. The same effect is seen in Figure 6 for the overall friction coefficient. The overall friction coefficient can be defined as single friction coefficient for the entire wellbore. Here, the change in friction coefficient is the resultant effect of contact surface between the borehole and the bottom hole assembly. This effect vanishes gradually as the bottom hole assembly passes through the buildup section.

Question that should be answered are: Why should the friction coefficient be calculated for the friction analysis? Why is the friction force not enough for this analysis? Because in some cases the friction force increases due to change in well geometry, for example, increase in dogleg angle. Using a wellbore friction model will help to distinguish the effect of other factors from the friction coefficient increments.

For tripping in, the estimated friction force and overall friction coefficient show a significant increase as the tight hole occurs during the tripping in process, as shown in Figures 7 and 8, respectively. Based on these two parameters, one could possibly detect the onset of pipe stuck in a well. Figures 5 and 6 do not convey much information on a tight hole. The calculated overall friction coefficient during the tripping in process may be applied as an efficient means to detect a possibly tight hole. A rapid increase in friction force was seen while the well geometry had a straight holding angle. The reason that this phenomenon was not observed during the tripping out period is probably because the collapse and tight hole occurred as a result of lower ECD due to swabbing when tripping out and time effects on the formation.

Conclusions

- The effect of differential pressure on value of friction force is considerable. This results in more forces on the drillstring sticking to the wellbore. This can be seen from higher values of the real-time calculation of the friction coefficient.
- In friction analysis, the Buoyancy effect should be treated precisely. In tripping in when the drillstring is partially filled with drilling fluid, ignoring this effect could results in erroneous estimation of the overall friction coefficient.
- Using friction model instead of friction force provides the possibility to see the effect of well geometry on the value of the friction force.
- While tripping in the as in the example shown herein an increase in the real-time friction coefficient indicated tight hole. [Please, check this sentence…]
- The collapse and tight hole in this case study might have been initiated after the drill string was pulled out due to swabbing and time effects of the collapsed formation.

Nomenclature

ΔL	length of element
C_S	contact surface correction factor
d_i	inner diameter of drillstring
d_o	outer diameter of drillstring
F	tension force
F_N	normal force
FF	friction force
w	unit pipe weight
α	inclination angle
β	buoyancy factor
γ	contact surface angle

θ	dogleg angle
μ	friction coefficient
ρ	density
φ	azimuth angle

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Figures

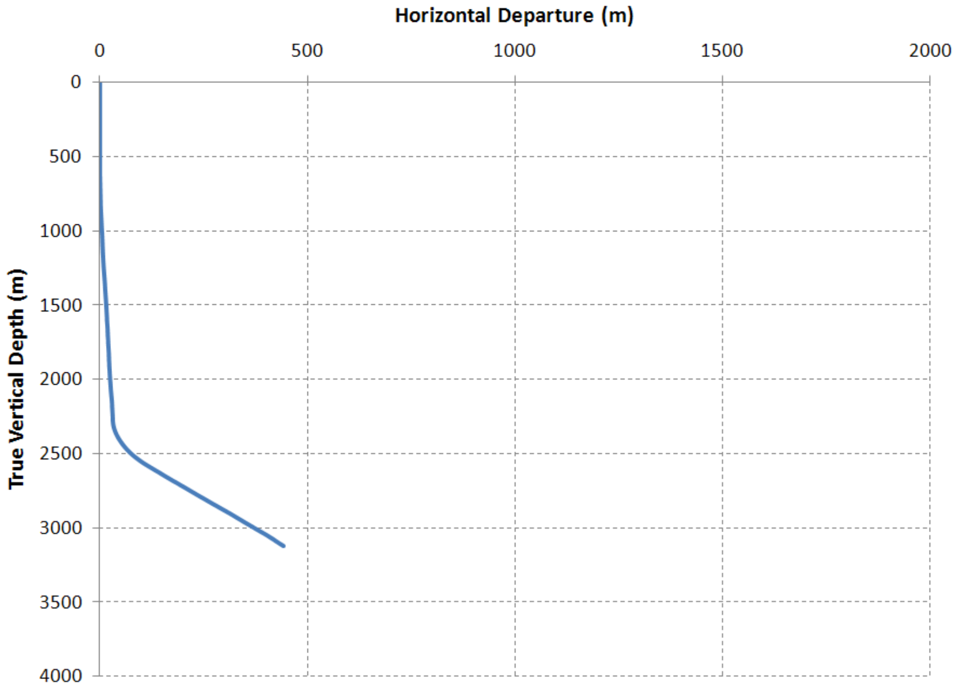

Figure 1: Well geometry before stuck pipe problem

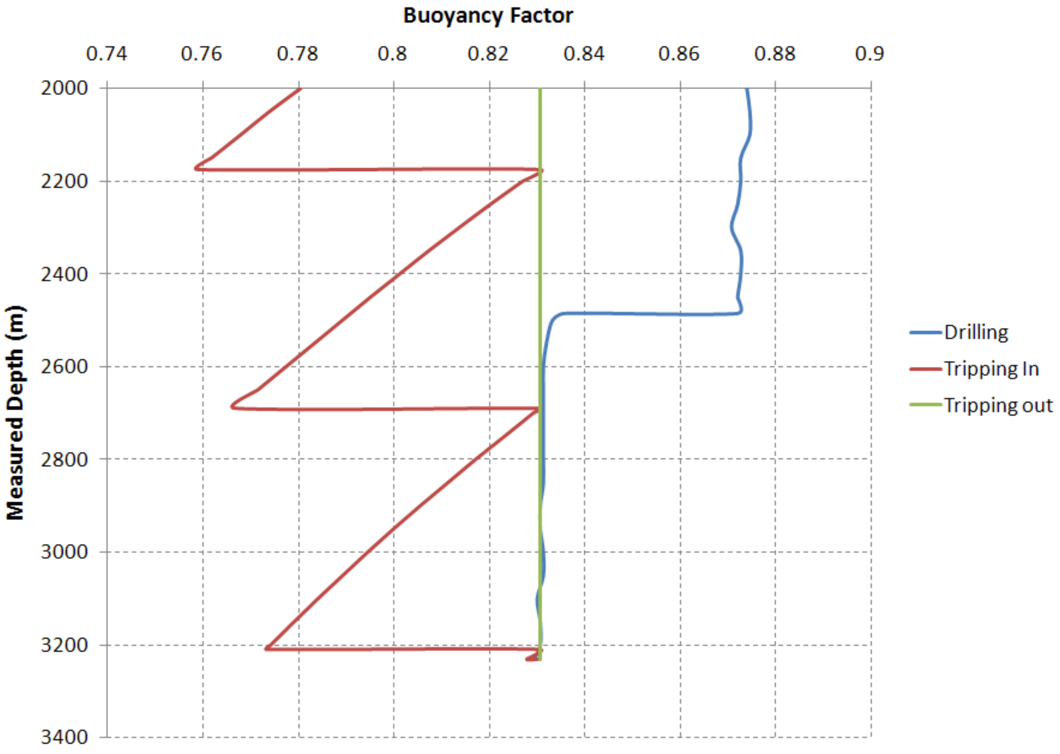

Figure 2: Buoyancy profile during different drilling operations

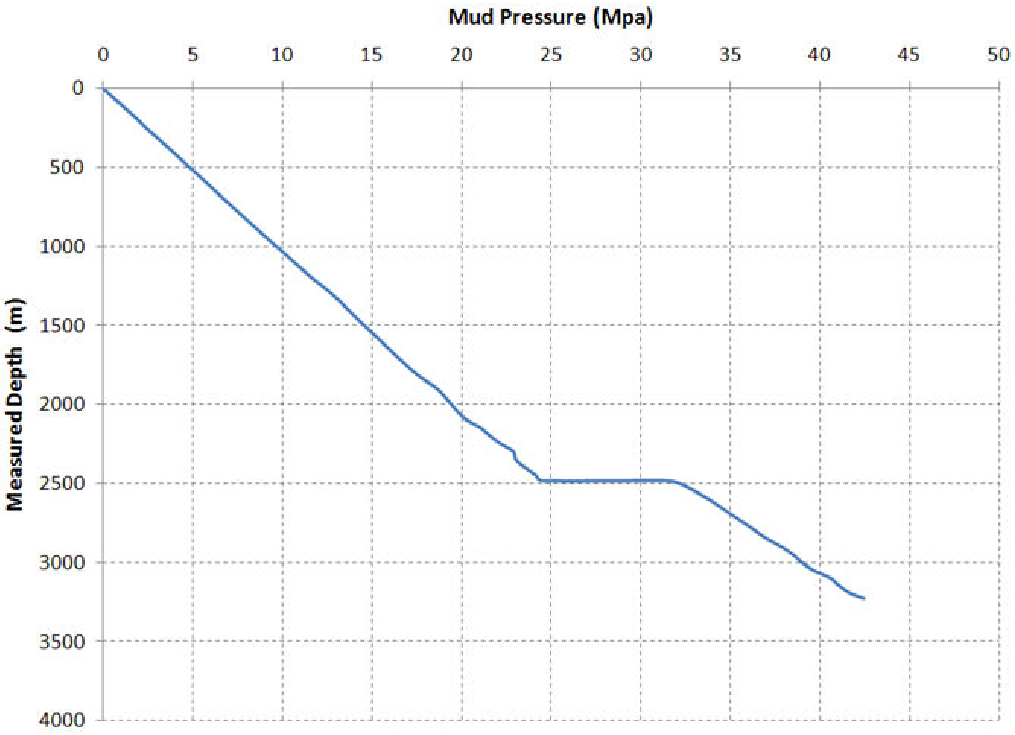

Figure 3: Mud pressure gradient versus measured depth during drilling operation

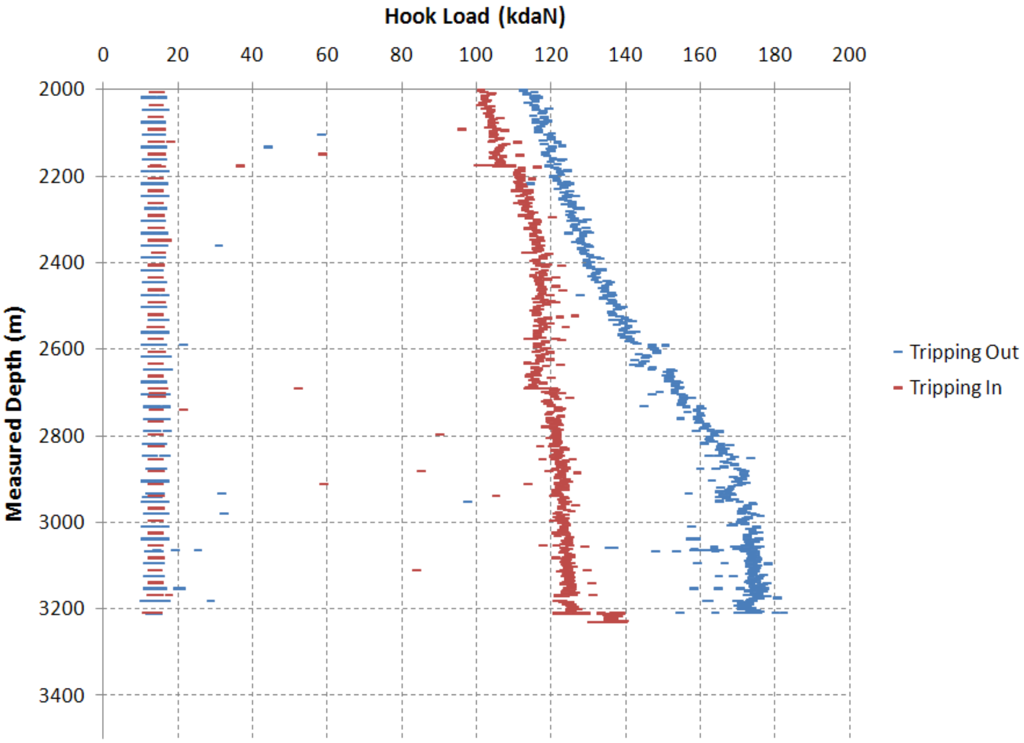

Figure 4: Hook load data versus measured depth during tripping in and out

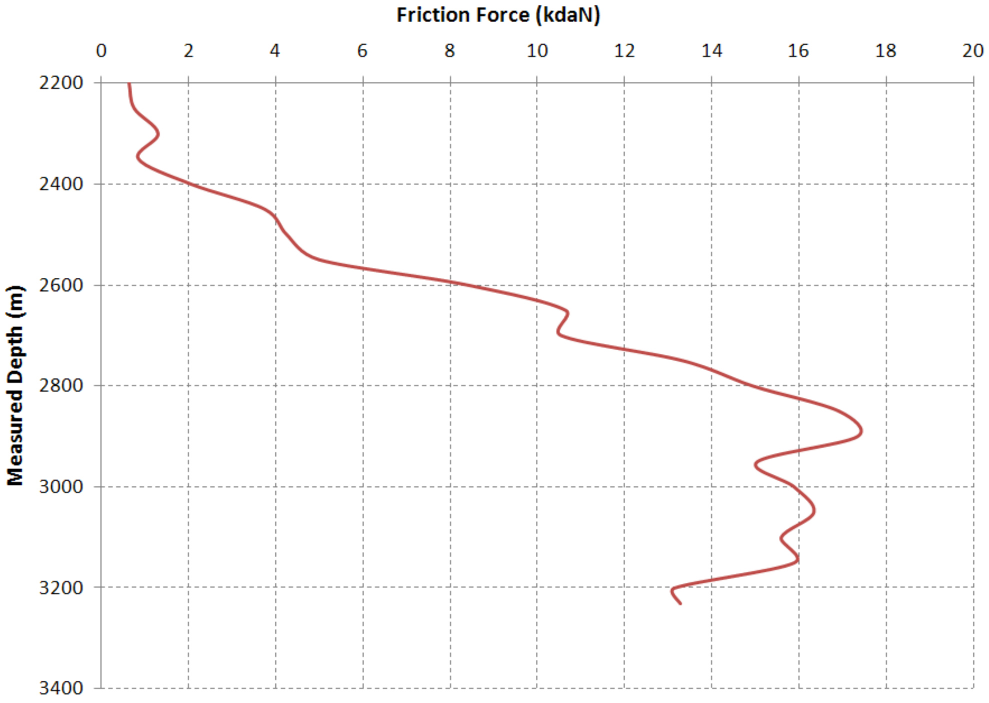

Figure 5: Friction force versus measured depth during tripping out

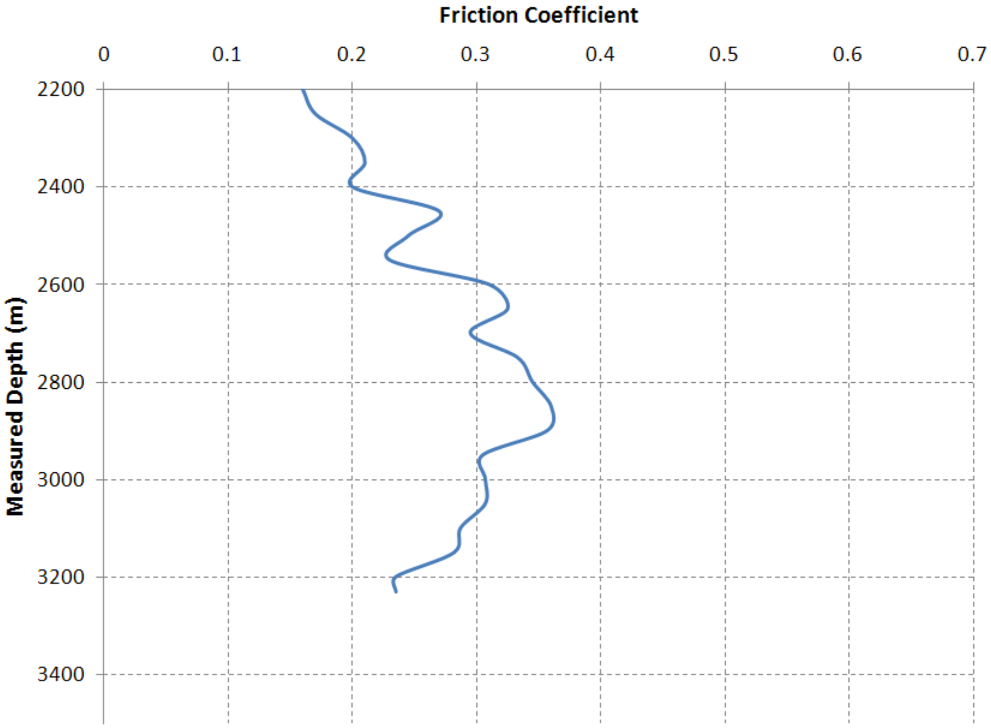

Figure 6: Overall Friction coefficient versus measured depth while tripping out

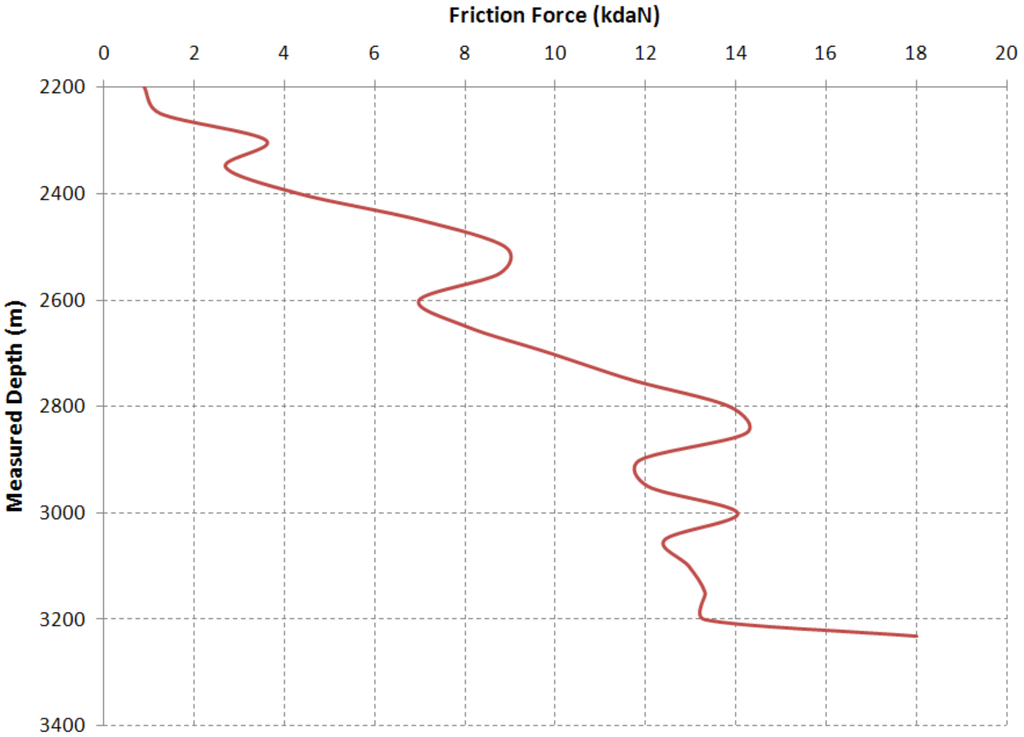

Figure 7: Friction force versus measured depth during tripping in

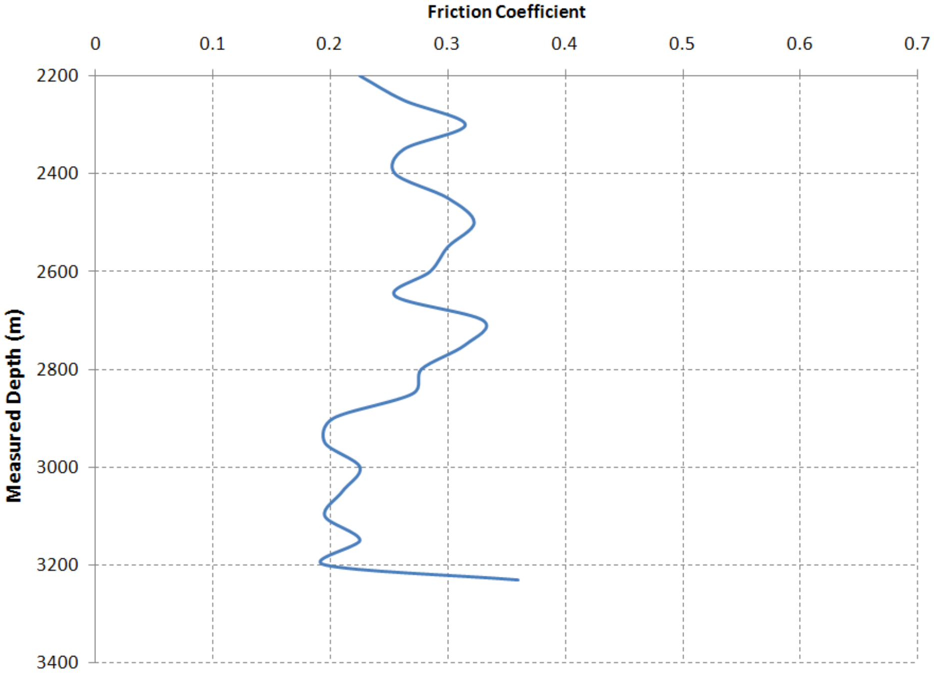

Figure 8: Overall Friction coefficient versus measured depth while tripping in