CHAPTER II
LITERATURE REVIEW

2.1 Specific Energy (SE)

In 1965, Teale proposed the first concept of specific energy in rock drilling. The specific energy (SE) is determined by the work done per unit volume excavated in unit pound per cubic inch (lb./in^3) written in eq.2.1. The specific energy consisted of two work terms, which are thrust (e_t) in lb./in^2 and rotary (e_r) in lb./in^2 as expressed in eq.2 and eq.3, respectively. The work of compression or thrust depends on down-hole weight on bit (DWOB) and area of bit (A_{Bit}). The rotary work is calculated from rotary velocity (RPM), down-hole torque (DTOR), rate of penetration (ROP) and bit area.

$$SE = \frac{total\ work\ input}{volume\ of\ excavated\ rock} \tag{2.1}$$

$$e_t = \left(\frac{DWOB}{A_{Bit}}\right) \tag{2.2}$$

$$e_r = \left(\frac{2\times\pi}{A_{Bit}}\right)\left(\frac{RPM\times DTOR}{ROP}\right) \tag{2.3}$$

Then, eq.2.1 becomes,

$$SE = \left(\frac{DWOB}{A_{Bit}}\right) + \left(\frac{2\times\pi}{A_{Bit}}\right)\left(\frac{RPM\times DTOR}{ROP}\right) \tag{2.4}$$

Because of dividing by A_{Bit}, the unit of specific energy is the same as the unit of pressure (lb./in^2). Moreover, specific energy is the variable that depends on the nature of rock called strength of rock, also known as mechanical specific energy (MSE). A main problem of MSE calculation is acquisition of down-hole parameters (DTOR and DWOB). However, the value of MSE still higher than confined compressive strength (CCS), which represents the force applied to a defined area A, necessary to deform the rock at bottom hole pressure (Bevilacqua *et al.*, 2013). Thus, the same formation at same bottomhole pressure has the same CCS. Regarding to the higher value of MSE than CCS, Armenta (2008) tried to improve the MSE equation by adding bit hydraulic term into MSE equation and called drilling specific energy (DSE) and Mohan *et al.* (2009) proposed hydro mechanical specific energy (HMSE).

2.2 Drilling Specific Energy (DSE)

DSE is the amount of energy required to destroy and remove underneath the bit a volume of rock, which depends on drilling and rock compressive strength. DSE calculation is shown in eq. 2.5, which includes three work terms, i.e. axial, torsional and bit hydraulic energies (Armenta, 2008). Then, DSE is expressed in both of mechanical and hydraulic terms, which make the result of calculation of DSE value close to CCS. The bit hydraulic term can be calculated in eq. 2.6, which requires a value of bit hydraulic power (HP_B) and bit coefficient (λ). The expression of HP_B in eq. 2.7 requires mud flow rate (Q) and pressure drop across the bit (ΔP_B). The pressure drop across the bit is obtained from a general equation of pressure drop along the pipe, which can be calculated by eq. 2.8. It requires drag coefficient (cd), mud density (ρ_m) and total flow area (A_t). This development was studied for solving the problem of MSE, which is mentioned before. Thus, mechanical effieicncy (EFF_M) will be applied to correct the value of DSE closes to CCS. In this research, DSE is chosen as the specifice energy calculation.

$$DSE = \left(\frac{480 \times DTOR \times RPM}{d^2 ROP} + \frac{4 \times DWOB}{d^2 \times \pi} + E_{hydraulic}\right) \times EFF_M \quad (2.5)$$

$$E_{hydraulic} = \left(\frac{-1{,}980{,}000 \times \lambda \times HP_B}{ROP \times A_{Bit}}\right) \quad (2.6)$$

$$HP_B = \frac{Q \times \Delta P_B}{1714} \quad (2.7)$$

$$\Delta P_B = \frac{8.311 \times 10^5 \times \rho_m \times Q^2}{C_d^2 \times A_t^2} \quad (2.8)$$

2.3 Hydro Mechanical Specific Energy (HMSE)

In 2009, Mohan *et al.* proposed HMSE, which is different from DSE in bit hydraulic term. There are four equations for calculating HMSE in four cases as follow: 1) the pilot bit is drilling simultaneously with the hole enlarging tool, 2) the pilot bit is only guiding the bit or the drilling involves a hole-opener with bull nose, 3) there is no hole-opener in the system, and 4) there is bicenter bit in the drilling. In this chapter reviews only the general form of HMSE, which is shown in eq. 2.9. W_A, W_B and W_C refer to three work terms, which are compression, rotation and bit hydraulic, respectively. The full equation of HMSE is shown in eq. 2.10. As the difference in the hydraulic term between DSE and HMSE, the two equations give the same trend but different value because the hydraulic term, which is very small when compared to the value of MSE.

$$HMSE = \frac{W_A+W_B+W_C}{Volume\ of\ rock\ drilled} \tag{2.9}$$

$$HMSE = \frac{DWOB}{A_{Bit}} + \frac{120\times\pi\times N\times DTOR}{A_{Bit}\times ROP} + \frac{1154\times\eta\times\Delta P_B\times Q}{A_{Bit}\times ROP} \tag{2.10}$$

2.4 Application of Specific Energy

MSE was developed by Teale (1965) for the purpose of tracking the drilling performance. The benefit of drilling performance determination is to optimize the drilling process, which can save the drilling time. The drilling efficiency is a parameter to explain the drilling performance and can be calculated by eq. (2.11). The perfect drilling process is the point that MSE is equal to (CCS), which means there is no loss in work input to drill a unit volume rock. However, the drilling efficiency is usually lower than one, which means there is no perfect drilling in the real operation. Figure 2.1 shows DSE application in drilling performance determination. The green circles in both of left and right figure represent the efficient drilling section, which ROP increase when WOB increase. The red circles represent the inefficient drilling section, which the change in ROP is not depends on the change in WOB. The inefficient drilling section means there is improper in applied WOB and bit size, which lead to loss in work input. However, DSE can be used for other purposes, such as determining the rock characteristic by combining with well logging data (porosity, resistivity and gamma ray) (Celada *et al.*, 2009). This research used DSE to determine the potential production zone, which is suitable zone for production by considering DSE together with well logging data.

$$Efficiency = \frac{confinded\ rock\ compressive\ strength}{specific\ energy} \tag{2.11}$$

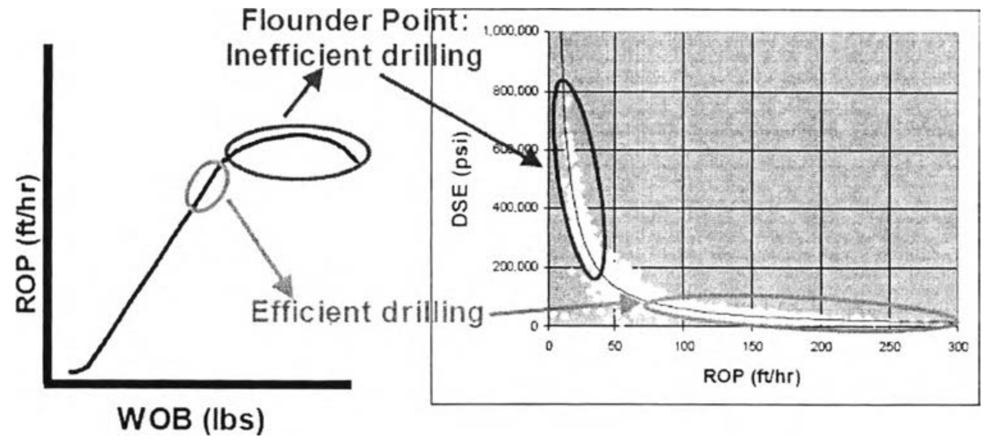


Figure 2.1 Drilling specific energy in determining efficient drilling zone (Armenta, 2008).

2.5 Down-hole Parameters

The down-hole parameters (DTOR and DWOB) are required in the accurate calculations of MSE, DSE and HMSE, but it is quite difficult to obtain and takes a long time. Fazaelizadeh (2013) suggested DTOR (Figure 2.2) and DWOB (Figure 2.3) calculations from the difference value between on and off bottom drilling using surface parameters. The summary of flow chart in Figure 2.2 and 2.3 is to find the on and off bottom operations. Then, uses the back calculation to calculate the value of DWOB and DTOR, which makes the measured hook load equal to calculated hook load and surface torque equal calculated torque, respectively. Although, this method gives the accurate DTOR and DWOB, it can delay the drilling operation for taking the on and off bottom data. Each time to measure on and off bottom data means the drilling operation is disturbed. Thus, the more point of data requires more delay in drilling time.

A new technology use sensors to measure DTOR and DWOB, but the method adds additional cost to the drilling (Junor, 2007). Thus, this research focuses on calculating DTOR and DWOB from the back calculation of available friction model, which uses the surface data and does not disturb the drilling operation. There are three friction models was studied in this research, which will be mentioned later.

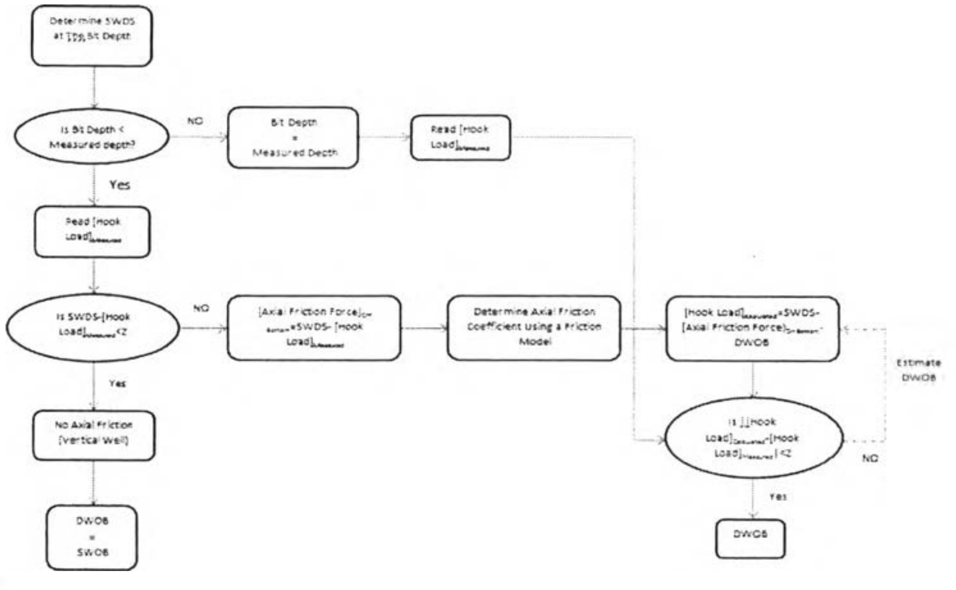


Figure 2.2 Flowchart of DWOB calculation (Fazaelizadeh, 2013).

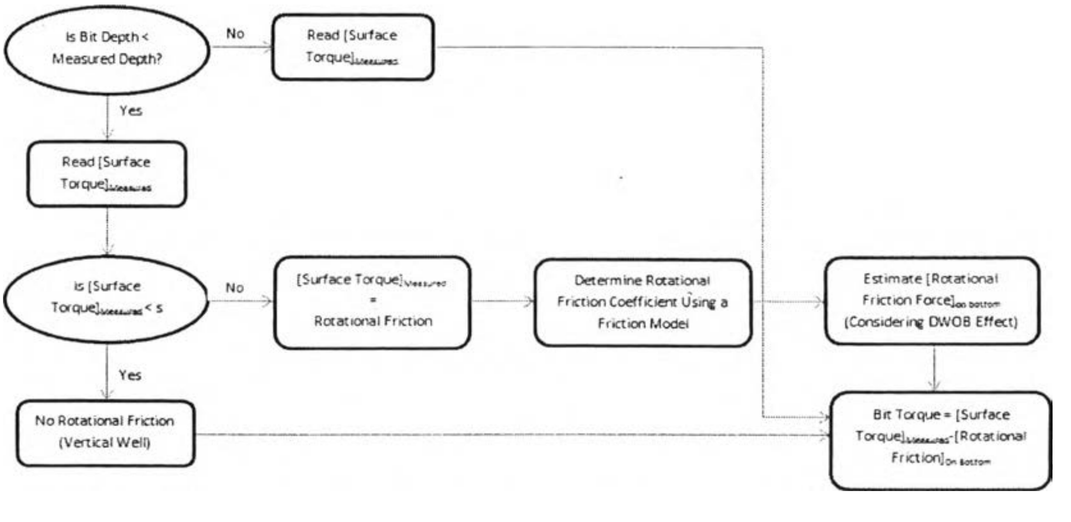


Figure 2.3 Flowchart of DTOR calculation (Fazaelizadeh, 2013).

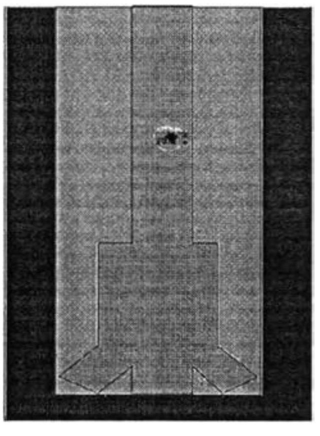
2.6 On and Off Bottom Drilling

2.6.1 On Bottom Drilling

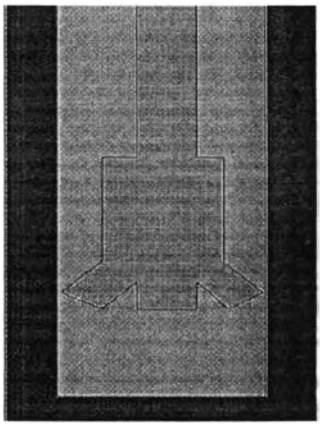
In the drilling, the bit engages to the formation at the bottom of borehole, normally called rotating on bottom. This is a normal drilling that there are both bit torque and weight on bit. Figure 2.4 (a) is bit position for on bottom drilling operation. The penetration will occur because the bottom of the bit attaches to the formation, where the force from bit can be transferred to the formation.

2.6.2 Off Bottom Drilling

Off bottom drilling means the bit does not engage to the formation or is floating from the formation normally called rotating off bottom (Figure 2.4 (b)). This drilling type normally occurs when a new stand of drilled pipe is added or back reaming operation. Weight on bit and bit torque are zero because the bit does not engage to the formation and there is no rate of penetration for this drilling because of no increment in hole depth.



(a)



(b)

Figure 2.4(a) Rotating on bottom and **(b)** rotating off bottom.

2.7 Fundamental Concept of Torque and Drag

In 1984, Johancsik *et al.* proposed the first concept of torque and drag calculation in a directional well. After that, the torque and drag model has been developed and used widely to help prediction and prevention of drilling problems that might occur during the drilling process (Mirhaj, 2011). However, there are problems with the accuracy of each model. There is no a model, which fit for every well shapes. An accurate model contains very complex mathematic equations, which are difficult to solve and a simple model cannot predict the accurate torque and drag in complex well shapes.

2.7.1 Normal Contact Force (N)

Normal contact force is defined as the perpendicular force that acting on the attached drill string on wellbore, so it occurs only in the area where the drill string attaches to wellbore and depending on drilling operations, buoyed weight of drill string and inclination. It is necessary in torque and drag analysis. Figure 2.5 shows forces acting on drill string.

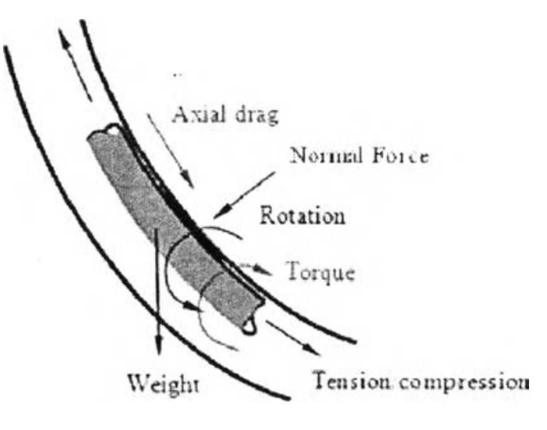


Figure 2.5 Forces acting on drill string (Fazaelizadeh, 2013).

2.7.2 Friction Coefficient (Friction Factor)

Friction coefficient is required for torque and drag calculation. The change in friction coefficient has a significant impact on torque and drag. For example, an increment in friction coefficient will increase hook load for pulling out of the hole case and decrease hook load for lowering pipe into the hole. The amount of increment or decrement in hook load due to the change of friction coefficient depends on an inclination of drill string, buoyed weight of drill string and formation types. For charging in torque, the increment of friction coefficient will increase the torque in both pulling out the hole and lowering pipe into the hole. Lesage *et al.* (1988) estimated friction coefficient along the wellbore in Johansick *et al.* model. The average of friction coefficient is in the range of 0.25 - 0.4, however, it can be between 0.05 and 0.5 in some severe conditions. A precise value of friction coefficient will help to calculate the accurate value of torque and drag.

2.7.3 Torque

Johansick *et al.* (1984) defined torque for the first time as a moment required to rotate the pipe as shown in Figure 2.6. Torque is calculated by multiplying sliding friction forces (F) with radius of drill string (r) at that section. The factors that have impact on sliding friction force are normal contact force and friction factor (μ). Normal contact force is equal to the contact of buoyed weight of drill string at that section ($w\Delta L$), which depends on the shape of attaching pipe to wellbore and the torque and drag model. Friction factor depends on type of formation, drill string and contact inclination between wellbore and drill string. Thus, torque will be varied on radius of drill string, normal contact force and friction factor.

2.7.4 Drag

Johansick *et al.* (1984) defined drag as the incremental force required to move the pipe up or down in the hole. Drag force is a proportional to weight of drill sting ($w\Delta L$) and friction factor (μ). The drag force is the summation of weight and friction of drill string in the movement axis. For picking up process, drill sting has more drag force than lowering drill string because of the direction of drilling weight when compared with the friction direction.

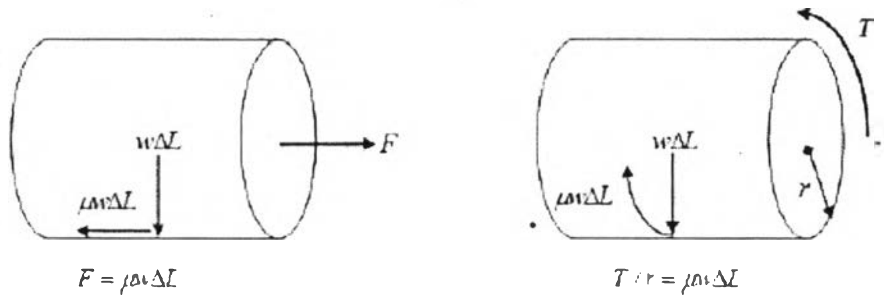


Figure 2.6 Drag force and torque acting on drill string (Fazaelizadeh, 2013) .

2.8 Torque and Drag Equations

2.8.1 Torque and Drag in 2-Dimensional Wellbore

Johansick *et al.* (1984) proposed the equations (2.12, 2.13 and 2.14) to calculate normal contact force (N), torque (T) and drag (F_n) in 2-dimensional wellbore, respectively. The positive sign in the drag calculation means the pipe is moving upward and becomes negative if moving downward. The weight of pipe in eq. 2.12 is buoyed weight (w_b), which can be calculated from eq. 2.13. $\bar{\alpha}$ in eq. 2.12 is the average inclination angle between element n and n+1. The practical calculation of torque and drag in drill string will begin at the bottom of drill string which is the bit. Then, the torque and drag are summed from the bottom of drill string to the top of drill string on the surface. The summation of torque and drag from the previous element are expressed as T_n and F_n in eq. 2.14 and 2.15, respectively. The subscription n and n+1 mean previous element (n) and next element (n+1). However, the results from this model do not match with the actual field data for the complex well shapes. Thus, the 3-dimension model is necessary to study for the better result.

Normal contact force

$$N = \left[\left(F_n + \Delta\Phi sin\bar{\alpha}\frac{\pi}{180}\right)^2 + \left(F_n\Delta\Phi\frac{\pi}{180} + w_b sin\bar{\alpha}\right)^2\right]^{\frac{1}{2}} \quad (2.12)$$

2-D torque

$$T_{n+1} = T_n + \mu N \quad (2.13)$$

2-D drag

$$F_{n+1} = F_n + w\cos\bar{\alpha} \pm \mu N \tag{2.14}$$

Buoyed weight

$$w_b = w \times \left(1 - \frac{\rho_m}{\rho_s}\right) \tag{2.15}$$

2.8.2 Torque and Drag in 3-Dimensional Wellbore

In the practical 3-D friction calculation, the friction calculation method is the same as 2-D, which the friction in each string element is summed from the bottom of drill string to the last string element at the surface. The net drag force, after adding hoisting system weight, is referred as the calculated hook load. The comparison of field and calculated hook load has to take into account of the effect of friction in the hoisting system and the measured data (Luke and Juvkam-Wold, 1993). In this chapter will review three models, which are Fazaelizadeh, Prurapark and Hareland models.

2.8.2.1 Fazaelizadeh's Model

In 2010, Fazaelizadeh et.al. published a 3-D analytical model for torque and drag. It contains two sets of equations, which are equations for straight and curve sections (eq. 2.16, 2.17, 2.18 and 2.19). In both straight and curve sections, the sign of friction term (the last term) is positive for pulling and negative for lowering the drill string. One different thing of this model from others is friction vector (Ψ). Aadnoy and Andersen (2001) proposed Ψ, which separates friction into axial and rotational (eq. 2.20). During the operation axial (V_h) and radial (V_r) velocities such as reaming and drilling, the axial friction will change into radial friction that means a lot of friction in drag calculation is reduced. In the curvature section, the friction is in an exponential form multiplied by dog leg angle (θ) which can be calculated by eq. 2.22. Where Φ refers to azimuth angle, α refers to inclination and n and n+1 refer to top and bottom of drill string element, respectively. This model is a simple calculation for torque and drag in 3-D wellbore based on soft string model. However, a finite element method is required to get the accurate value of the model (Wu and Hareland, 2012).

Torque and drag in straight section

$$F_{n+1} = F_n + w_b \Delta MD cos\alpha \pm \mu w_b \Delta MD sin\alpha sin\Psi \quad (2.16)$$

$$T_{n+1} = T_n + r\mu w_b \Delta MD sin\alpha cos\Psi \quad (2.17)$$

Torque and drag in curve section

$$F_{n+1} = F_n + F_n\left(e^{\pm\mu|\theta|} - 1\right)sin\Psi + w_b \Delta MD\left(\frac{sin\alpha_{n+1} - sin\alpha_n}{\alpha_{n+1} - \alpha_n}\right) \quad (2.18)$$

$$T_{n+1} = T_n + \mu r F_N |\theta_2 - \theta_1| cos\Psi \quad (2.19)$$

Calculation of friction vector (Ψ)

$$\Psi = tan^{-1}\left(\frac{V_h}{V_r}\right) \quad (2.20)$$

$$V_r = \frac{\pi r}{60} RPM \quad (2.21)$$

Calculation of θ

$$cos\theta = sin\alpha_{n+1} sin\alpha_n cos(\Phi_{n+1} - \Phi_n) + cos\alpha_{n+1} cos\alpha_n \quad (2.22)$$

2.8.2.2 Prurapark's Model

In 2009, Prurapark wrote 3-D friction calculation for well planning operation in his dissertation. The friction model can be expressed in lowering the drill string and pulling the drill string operations. Each operation contains three well trajectories, which are build-up, drop off and hold section. This review contains only lowering the drill string operation, which is used in the friction calculation on this research. In the calculation, R refers to radius of curvature. This model base on the changing in normal contact force (N) for each well trajectories and N multiplied by friction coefficient (μ) is equal friction force. The positive sign of N means drill string contacts at the lower site of wellbore at this section and negative for contacting upper wellbore. The term of R_{turn} is an expression of radius for left and right turns of drill string. The calculation of R and R_{turn} are be shown in an Appendix B.

Build-up section

Normal contact force in build section can be calculated as eq. 2.23 and Figure 2.7 will illustrate the force in build-up section.

$$N = W_b cos(\alpha) + \frac{F_{n+1}(\alpha)}{R} \tag{2.23}$$

Axial force in build section can be calculated as:

For N > 0 and ($\alpha_1 \geq \alpha \geq \alpha_0$)

$$\frac{d(F)}{d(\alpha)} = \mu\left\{\sqrt{\left[W_b cos(\alpha) + \frac{F_{n+1}(\alpha)}{R}\right]^2 + \left[\frac{F_{n+1}(\alpha)}{R_{turn}}\right]^2}\right\} R - W_b R sin(\alpha) \tag{2.24}$$

For N < 0 and ($\alpha_2 \geq \alpha \geq \alpha_1$)

$$\frac{d(F)}{d(\alpha)} = \mu\left\{-\sqrt{\left[W_b cos(\alpha) + \frac{F_{n+1}(\alpha)}{R}\right]^2 + \left[\frac{F_{n+1}(\alpha)}{R_{turn}}\right]^2}\right\} R - W_b R sin(\alpha) \tag{2.25}$$

Note. α in build up section refers to 90-inclination of element n

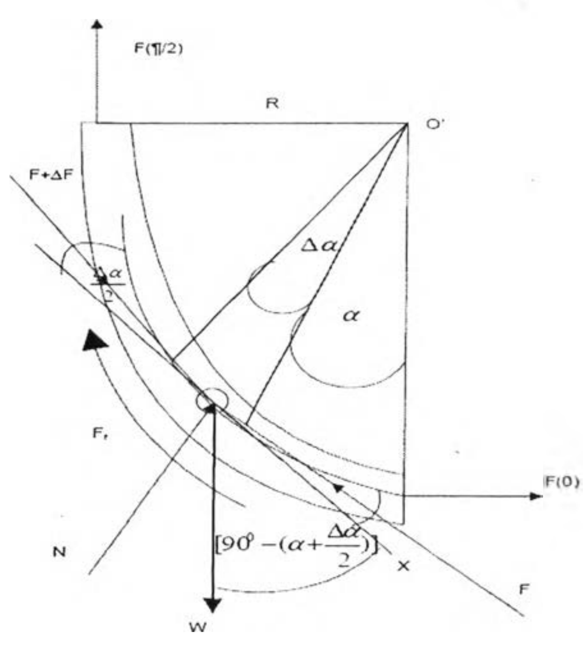


Figure 2.7 Forces applied to drill string in build-up section (Prurapark, 2009).

Hold Section

Normal contact force in hold section can be calculated as eq. 2.26 and Figure 2.8 will illustrate the force in hold section.

$$N_{total} \ = \ \sqrt{(W_b \sin(\alpha))^2 + \frac{F_{n+1}(\alpha)}{R}} \tag{2.26}$$

$$\Delta F = F_n - F_{n+1} = \mu N_{total} - W cos(\alpha) \tag{2.27}$$

Note. α in hold section refers to inclination of element n.

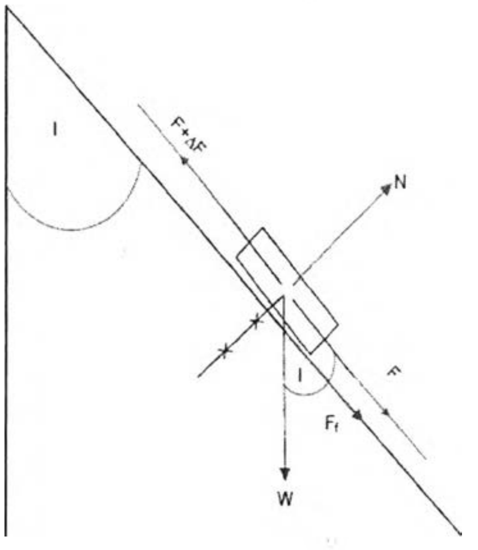


Figure 2.8 Forces applied to drill string in hold section (Prurapark, 2009).

Drop Section

Normal contact force in drop section can be calculated as eq. 2.28 and Figure 2.9 will illustrate the force in drop section.

$$N \ = \ W_b sin(\alpha) - \frac{F_{n+1}(\alpha)}{R} \tag{2.28}$$

Axial force in drop section can be calculated as:

For N > 0 and ($\alpha_1 \geq \alpha \geq \alpha_0$)

$$\frac{d(F)}{d(\alpha)} = \mu\left\{\sqrt{\left[W_b sin(\alpha) - \frac{F_{n+1}(\alpha)}{R}\right]^2 + \left[\frac{F_{n+1}(\alpha)}{R_{turn}}\right]^2}\right\} R - W_b R cos(\alpha) \qquad (2.29)$$

For N < 0 and ($\alpha_2 \geq \alpha \geq \alpha_1$)

$$\frac{d(F)}{d(\alpha)} = \mu\left\{-\sqrt{\left[W_b sin(\alpha) - \frac{F_{n+1}(\alpha)}{R}\right]^2 + \left[\frac{F_{n+1}(\alpha)}{R_{turn}}\right]^2}\right\} R - W_b R cos(\alpha) \qquad (2.30)$$

Note. α in drop section refers to inclination of element n.

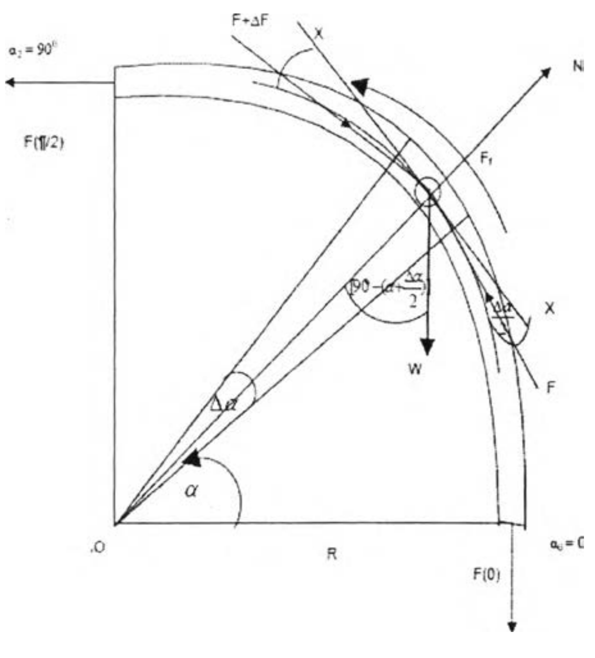


Figure 2.9 Forces applied to drill string in drop section (Prurapark, 2009).

2.8.2.3 Hareland's Model

In 2014, Hareland *et al.* published field tests of DWOB from both calculation model and commercial sensor. The Fazaelizadeh's model was used for the DWOB and friction coefficient calculation. The model was tested with two wells and the results close to the commercial sensor, thus this model is suitable for DWOB and friction coefficient calculation. The model consists of two well shapes, which are straight section and curve section (eq. 2.31-2.35). The term $\beta_i w_i \Delta L_i$ refers to buoyed weight of this drill string element and φ for azimuth degree.

Drag in straight section

$$F_i = F_{i-1} + \beta_i w_i \Delta L_i cos\alpha_i - \mu\beta_i w_i \Delta L_i sin\alpha_i \tag{2.31}$$

Drag in curve section for tension force, $F_{i-1}>0$

$$F_i = F_{i-1} \times e^{-\mu|\theta_i|} + \beta_i w_i \Delta L_i \times \left(\frac{sin\alpha_i - sin\alpha_{i-1}}{\alpha_i - \alpha_{i-1}}\right) + \mu\beta_i w_i \Delta L_i \times \left(\frac{cos\alpha_i - cos\alpha_{i-1}}{\alpha_i - \alpha_{i-1}}\right) \tag{2.32}$$

$$\theta_i = arccos(sin\alpha_i sin\alpha_{i-1} \cos(\Phi_i - \Phi_{i-1}) + cos\alpha_i cos\alpha_{i-1}) \tag{2.33}$$

Drag in curve section for compression force, $F_{i-1}<0$

$$F_i = F_{i-1} + \beta_i w_i \Delta L_i cos\alpha_i - \mu F_n \tag{2.34}$$

$$F_n = \left[\begin{array}{c} \left(F_{i-1}(\Phi_i - \Phi_{i-1}) sin\left(\frac{\alpha_i - \alpha_{i-1}}{2}\right)\right)^2 + \\ \left(F_{i-1}(\alpha_i - \alpha_{i-1}) + \beta_i w_i \Delta L_i sin\left(\frac{\alpha_i - \alpha_{i-1}}{2}\right)\right)^2 \end{array}\right]^{\frac{1}{2}} \tag{2.35}$$

For the curve section, the model will separate the calculation into two cases, which are compression and tensile forces at the bottom of drill string element. The compression force, which means the value of the force at the bottom of the string element is negative, which occur when the element is found near the bit. The tensile force, which means the value of the force at the bottom of string element is positive when the element is far from the bit until the last element is at surface.

Field Calibration

Hareland *et al.* (2014) also suggested the calibration of field hook load by using three corrections, which are Sheave effect (HL_a), Static Hook effect (HL_b) and Standpipe pressure effect (HL_c). The summation of the three corrections is the adjusted hook load, which is used in the calculation of friction coefficient and DWOB. HL_f, η and n in sheave effect calculation (eq. 2.36) mean field hook load, hook efficiency and number of line in hoisting system, respectively. HL_s in eq. 2.37

is hook weight. χ in eq. 2.38 means the coefficient from theory standpipe pressure and field standpipe pressure and Spp. refers to standpipe pressure.

Sheave effect

$$HL_a = \frac{HL_f(1-\eta^n)}{n(1-\eta)} \tag{2.36}$$

Static Hook effect

$$HL_b = \frac{HL_s(1-\eta^n)}{n(1-\eta)} \tag{2.37}$$

Standpipe pressure effect

$$HL_c = 5.095 \times 10^{-5} \times Spp. \times id^2 \tag{2.38}$$

Adjusted Hook load

$$HL = HL_a - HL_b - \chi HL_c \tag{2.39}$$

2.8.3 DTOR and DWOB Relationship

In 1992, Pessier and Fear published the relationship between DTOR, DWOB, bit diameter and friction coefficient as expressed in eq. 2.40.

$$DTOR = \frac{1}{36}\mu \times d \times WOB \tag{2.40}$$

2.9 Well Logging

Although seismic is the most famous method that is used in determining subsurface structure, it cannot give information of lithology. The methods to get the information of lithology are core recovery and well logging. The cost of core recovery is too expensive, especially in the deep well, so the well logging is a better choice in getting the formation parameters. The well logging will be done to record the structure of drilled reservoir to find the probability of hydrocarbon reserved. The purposes of well logging are to (Shankar, 1999), identify of reservoir, estimate of hydrocarbon in place and estimate recoverable hydrocarbon.

Well logging tools are equipment that continuously record the reservoir parameters with depth. It is done after finishing the drilling and removing drill string from the borehole. Generally, the logging data, that always recorded, are resistivity, neutron porosity and gamma ray.

2.9.1 Resistivity Logs (R-Logs)

Resistivity logs are used to measure the electrical resistivity of the formation. The tools will emit the current and measure the returning current after emitting. The formation resistivity usually falls in the range of 0.2 to 1000 ohm (Shankar, 1999). The information of resistivity can be interpreted as fluid inside formation, such as brine water (low resistivity), oil and gas (both show high resistivity). Moreover, shale (low resistivity) and dense rock (very high resistivity) can be determined by resistivity log (Schuster and Riboud, 1971). Figure 7 show the principle resistivity logging.

2.9.2 Neutron Porosity

The concept of neutron porosity uses the unstable isotopes. Neutron will be emitted to the formation each time to collide with nuclei of atoms in the formation. The neutrons lose their energy to nuclei and excite the nuclei of atoms in the formation (Shankar, 1999). Thus, the detection in energy of neutron can describe the porosity of the formation. Figure 2.10 shows the principle of neutron logging.

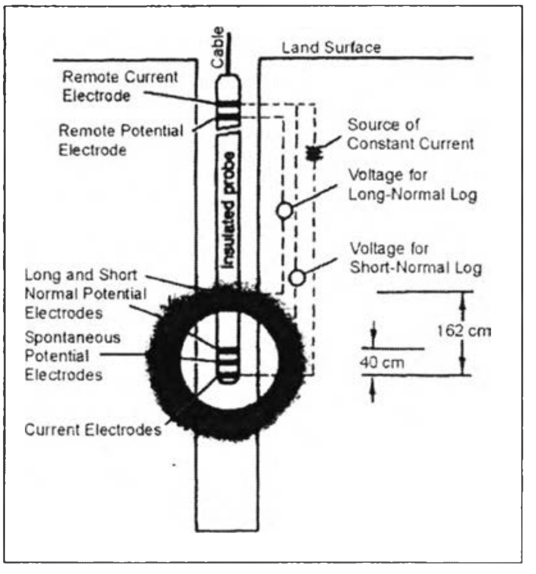


Figure 2.10 Principle of resistivity log (Wightman *et al.*, 2003).

2.9.3 Gamma Ray

This logging method will detect three main radioactive elements, which emit gamma ray in a down-hole condition. The three main elements are Potassium (K40), Uranium (U238) and Thorium (T32). The gamma logs provide a record of total gamma radiation detected in a borehole and are useful over a very wide range of borehole conditions because the gamma ray radiation depends on the type of formation such as shale shows high gamma ray and petroleum reservoir shows low gamma ray (Wightman *et al.*, 2003).

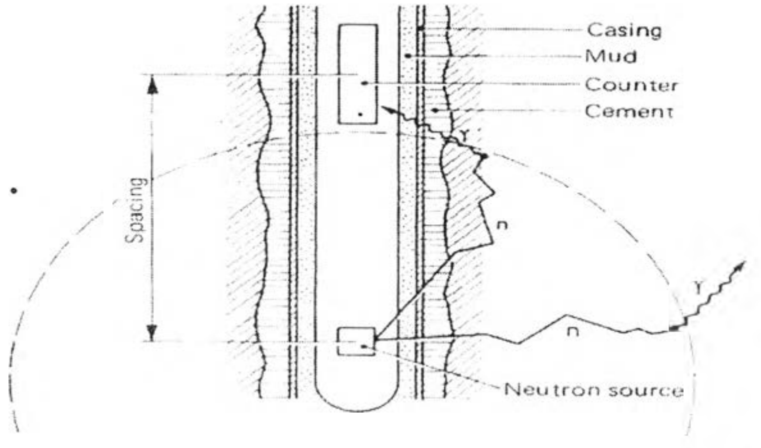


Figure 2.11 Principle of neutron logging (Shankar, 1999).