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WALK RATE PREDICTION FOR SLIMHOLE DRILLING IN THE GULF OF THAILAND

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Petroleum Engineering
Department of Mining and Petroleum Engineering
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Thesis Title	WALK RATE PREDICTION FOR SLIMHOLE DRILLING IN THE GULF OF THAILAND
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Field of Study	Petroleum Engineering
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การขุดเจาะเข้าไปในแหล่งกักเก็บปิโตรเลียมสำหรับประเทศไทยนั้นจำเป็นต้องมีการควบคุมอัตราการเบี่ยงเบนทิศทางของหัวเจาะให้มีค่าน้อยตามที่กำหนดเพราะขนาดของเป้าหมายนั้นมีขนาดเล็ก แหล่งกักเก็บปิโตรเลียมของไทยนั้นมีอุณหภูมิสูงกว่าระดับปกติมาก ทำให้ไม่สามารถใช้อุปกรณ์การควบคุมทิศทางเหมือนที่ใช้ในการขุดเจาะโดยทั่วไปได้ มากกว่าห้าเปอร์เซ็นต์ของหลุมที่เจาะในแต่ละปีไม่สามารถควบคุมอัตราการเบี่ยงเบนทิศทางของหัวเจาะให้เข้าไปในเป้าหมายได้ทำให้ต้องหยุดการขุดเจาะและดึงก้านเจาะออกมาเพื่อเปลี่ยนชุดอุปกรณ์ใหม่ที่คาดว่าสามารถใช้เบี่ยงทิศทางหัวเจาะให้เข้าสู่เป้าหมาย วิทยานิพนธ์ฉบับนี้จึงมุ่งศึกษาเพื่อบ่งชี้ว่ามีปัจจัยอะไรบ้างที่มีผลกระทบต่อการเบี่ยงเบนทิศทางของหัวเจาะและมีผลกระทบมากน้อยเพียงใด จากนั้นได้ทำการสร้างตารางการคาดคะเนอัตราการบี่ยงเบนทิศทางของก้านเจาะแต่ละแบบ เพื่อให้เราสามารถเลือกใช้ได้อย่างเหมาะสมและทำให้การขุดเจาะนั้นเข้าเป้าหมายตามที่กำหนด ทั้งนี้จะสามารถลดค่าใช้จ่ายในการขุดเจาะปิโตรเลียมได้

วิทยานิพนธ์ฉบับนี้ได้ใช้สถิติเชิงพรรณนา คือค่าร้อยละ ค่ามัธยฐาน และค่าเฉลี่ย ในการวิเคราะห์ข้อมูลจริงซึ่งเก็บตัวอย่างมาจากหลุมปิโตรเลียม 495 หลุมที่เจาะในปี ค.ศ. 2006 ถึง ค.ศ. 2008 โดยผลกระทบของแต่ละปัจจัยถูกแสดงและเปรียบเทียบเพื่อสามารถคาดการณ์อัตราการเบี่ยงเบนทิศทาง

ผลของการวิเคราะห์ข้อมูลเกี่ยวกับการบี่ยงเบนทิศทาง แสดงให้เห็นว่ามีปัจจัยดังต่อไปนี้ที่มีผลกระทบกับการเบี่ยงเบนทิศทางตามลำดับมากน้อย ได้แก่ ลักษณะของหัวขุดเจาะ ความเอียงของหลุมที่เจาะ ขนาดรอบวงของอุปกรณ์ในก้านเจาะ ค่าอัตราการหมุนก้านเจาะ แรงที่กดก้านเจาะ ตำแหน่งและการจัดเรียงชุดอุปกรณ์ในก้านเจาะ และความลึกของหลุมที่เจาะ ซึ่งค่าของผลกระทบมีขนาดเท่ากับ 0.26, 0.24, 0.20, 0.19, 0.18, 0.161 และ 0.160 องศาต่อหนึ่งร้อยฟุต ตามลำดับ และผลของอัตราการเบี่ยงเบนทิศทางของก้านเจาะที่คาดคะเนได้จากวิทยานิพนธ์ฉบับนี้ มีค่าใกล้เคียงกับค่าจริงมากโดยมีผลต่างเพียงแค่ 0.05 องศาต่อหนึ่งร้อยฟุต

ภาควิชา วิศวกรรมเหมืองแร่และปิโตรเลียม ลายมือชื่อนิสิต....................

สาขาวิชา วิศวกรรมปิโตรเลียม ลายมือชื่ออ.ที่ปรึกษาวิทยานิพนธ์หลัก....................

ปีการศึกษา 2553

507 16070 21 : MAJOR PETROLEUM ENGINEERING

KEYWORDS : WALK RATE PREDICTION / DRILLING

DARARAT AMPONPUN: WALK RATE PREDICTION FOR SLIMHOLE DRILLING IN THE GULF OF THAILAND. ADVISOR: ASSISTANT PROFESSOR JIRAWAT CHEWAROUNGROAJ, Ph.D., 91 pp.

When drilling petroleum well into the reservoir section in the Gulf of Thailand, the bit walk rate has to be kept at minimum because of the narrow target. Meanwhile the steerable tool cannot be used to directly control the hole direction because it cannot function in high temperature as in the Gulf of Thailand's reservoir. More than five percent of the wells drilled per year were pulled out of hole due to unable to keep the walk rate into the acceptable range. Then different bit design or different bottom hole assembly (BHA) was replaced to assure hitting target zones. This study was performed to address the factors that have influence on the bit walk, summarize their effects, and create the walk rate prediction table that can be used as a guideline for better pre-job planning such as BHA design and bit selection to reduce the number of trips for assembly changes which means saving cost in drilling wells.

The actual field data of 495 wells drilled from year 2006 to year 2008 which composed of 17,625 survey station points was used in the study. By using the statistical tools including percentile, median and mean, the effect of each parameter to the walk rate could be defined and compared, and the walk rate value could be predicted.

The study results indicated that the walk rate was influenced by the bit model, hole angle, AGS setting, RPM WOB, extension length and TVD depth in an average value of 0.26, 0.24, 0.20, 0.19, 0.18, 0.161 and 0.160 deg/100ft respectively. The walk rates predicted from this study were very close to the actual walk rates with less than 0.05 deg/100 ft discrepancies.

Department: Mining and Petroleum Engineering Student's Signature: Darat Ampo

Field of Study: Petroleum Engineering Advisor's Signature: Jirawat Chewaroungroaj

Academic Year: 2010

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LIST OF ABBREVIATIONS

AGS	Adjustable Gauge Stabilizer
BHA	bottom hole assembly
HWDP	Hevi-weight Drill Pipe
LWD	Logging while Drilling
MD	Measured Depth
MWD	Measurement while Drilling
OD	Outer Diameter
PDC	Polycrystalline Diamond Compact
ROP	Rate of Penetration
RPM	revolutions per minute
TVD	True Vertical Depth
WOB	weight on bit

CHAPTER I
INTRODUCTION

The reservoir in Gulf of Thailand has high temperatures and the downhole directional control tool, mud motor, cannot be used to drill to the target depth in this reservoir section due to its limitation on working temperature from the rubber part. The adjustable gauge stabilizer (AGS) is instead used to control the well inclination, with no downhole tool available to directly control the direction of the well. The well design for drilling the reservoir is a tangent section with a small or no change in hole angle, and no change in hole direction.

When drilling a vertical well or a low inclination well, the change in azimuth or the bit walk will not have much effect on its departure and when drilling a directional well, the degree of walk rate which normally in decimal per 100ft can be easily corrected with mud motor in sliding mode. Not like in the Gulf of Thailand where the mud motor cannot be used and more than 0.3 deg/100ft of walk rate will definitely walk the BHA outside the standard Gulf of Thailand ’s target. Therefore in the Gulf of Thailand, it has become critical to understand what are the main factors affecting the walk rate and how to control them.

From year 2006-2008 around a thousand wells were drilled in the Gulf of Thailand using AGS, and more than 60 runs were pulled out of hole due to unable to control the walk rate into the acceptable range as shown in Figure 1-1. Then different bit design or different bottom hole assembly (BHA) was replaced to assure that every targets were achieved. Figure 1-2 showed the average walk rate of wells drilled from year 2006-2008. The preferred walk rate in the Gulf of Thailand is -0.1 to 0.1 deg/100ft. Note that the average walk rate presented is calculated from azimuth differences between the run end and the run start divided by total interval drilled.

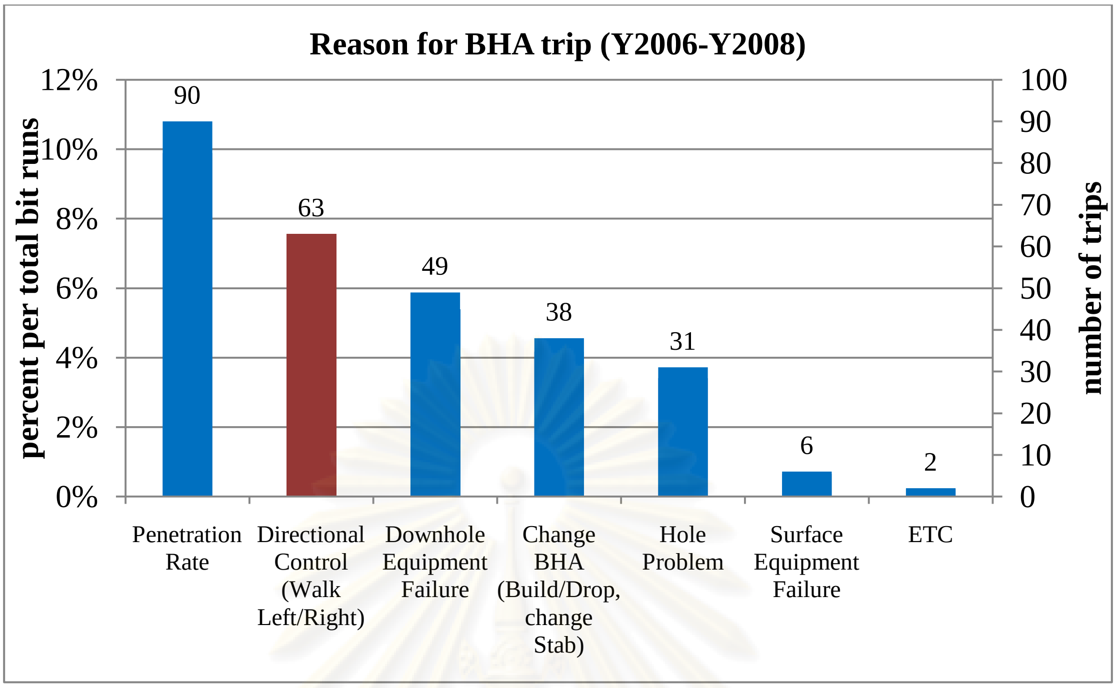


Figure 1-1: Summary of reasons for BHA trip in 6-1/8”section, Southern Pattani basin, Gulf of Thailand from year 2006 to 2008.

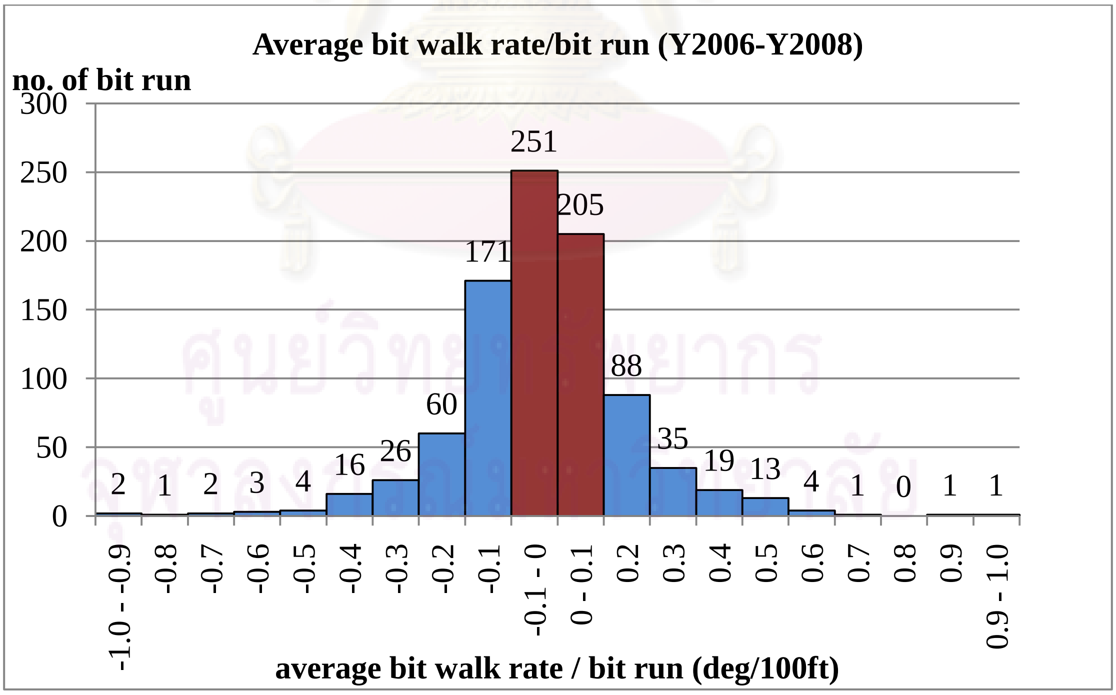


Figure 1-2: The average bit walk rate per each bit runs, Southern Pattani basin, Gulf of Thailand from year 2006 to 2008.

This thesis carried out to address the factors influence the bit walk, summarize theirs effects, and create the walk rate prediction tool in order to use as a guideline for better pre-job planning such as BHA design and bit selection to reduce the number of trips for assembly changes.

Past studies related to the bit walk rate were reviewed and parameters that effecting bit walk could be categorized into bit model, bottom hole assembly (BHA) configuration, wellbore trajectory, formation strength and anisotropy and drilling parameters. The actual data from wells drilled in year 2006 to year 2008 was collected and analyzed, and 495 wells of data that using three typical bit models and three standard BHA configurations were used in the study. Statistic tools; median and percentile were used for studying the influence of each parameter to the walk rate. The walk rate prediction table was created using these statistical values.

This thesis paper consisted of five chapters. The review of past studies on parameters affecting bit walk and walk rate prediction was outlined in Chapter 2. Chapter 3 explained the definition of bit walk, the parameters influenced bit walk and reviewed the standard drilling operations in the Gulf of Thailand. Chapter 4 presented what parameters had included in this walk rate study. The relationships of each parameter and the walk rate were established and discussed. The walk rate prediction table and recommended parameters for walk rate correction was presented together with the validation of the walk rate prediction table. And thesis's conclusions and recommendations were presented in the last chapter.

CHAPTER II
LITERATURE REVIEW

For decades many studies have been carried out to address and to understand the factors influencing the bit walk of the rotary BHA in order to be able to predict the walk rate, hence chance of hitting the targets is increased. The factors that have been addressed and studied including bit model, BHA configurations, formation strength and anisotropy, well angle and curvature and drilling parameters. The studies have been performed using actual field data observation and analysis, or three-dimensional computer model.

Perry (1986) conducted a field data observation and analysis to study the effect to bit walk from different bit profiles and drilling parameters. The study based on the average run walk rate of 206 bit runs of 8-1/2" rotary BHA drilled in the Gulf of Thailand. There were five bit profiles (A-E), ranging from very flat to ballistic profile used in his study. The change of walk rate affected from variation of weight on bit (WOB) and drilling string rotational speed (RPM) was observed and analyzed.

Perry concluded that bit profile, WOB and RPM had an effect on the walk rate. From the average run walk rates of each bit profile, different bit profiles gave different average walk rates ranging from 0.37 deg/100ft to the left to 0.4 deg/100ft to the right, and the ballistic bit profiles gave more left walk tendency compared to the flat profiles. Varying WOB and RPM caused the walk rate to change, and with most bit profiles, bit usually walked left at their optimum drilling parameters of 8-17 klbs WOB and 190-220 RPM.

Bannerman (1990) performed the walk rate prediction for the Alwyn North field, North Sea, based on 23 well data previously drilled in same area. Field data analysis and three-dimensional computer model were used for his study. By analyzing the data for each well in 17-1/2" and 12-1/4" sections, for example, the bit profile used, the average hole angle and the formation changes then an attempt was made to explain the variation of walk rates from well to well. The studied found that the walk rate was affected by bit profile and for the same bit profile, well angle and formation had affected the bit walk.

Bannerman used three-dimensional computer model, ORFHEE 3D to calculate the walk rate of the wells that had already drilled. Then coefficient numbers were adjusted to match the calculated walk rate and the actual walk rates. With selected coefficient numbers, the walk rate prediction model had 42% of the cases that the discrepancy between predicted value and actual value is less than 0.06 deg/100ft.

Chen, Collins and Thomas (2008) used three-dimensional computer model to calculate bit walk rate with consideration of bit gauge geometry, hole size, formation compressive strength, steering mechanism, bit rotational speed, penetration rate and dogleg severity. The study focused on PDC bit drilled with steerable system. Conclusion from the analysis and field application was that the walk of PDC bit depends on many factors including bit model (the cutting structure geometry, gauge/sleeve geometry), steering mechanism, BHA configuration, formation type and anisotropy, hole enlargement and hole shape.

From the walk rate study of Perry and Bennerman using field data observation and analysis, the following the parameters including 1) bit profile, 2) drilling parameters (RPM, WOB), 3) hole angle, and 4) formation changes had been included in the study and they were concluded to have affect to the bit walk in their drilling environments. This thesis studied the walk rate of the slimhole drilling in the Gulf of Thialand similar to the study of Perry and Bennerman, but BHA configuration including the stabilizer placement and size was also included in the study and the average walk rate of every survey stations were used for the analysis.

CHAPTER III
THEORIES AND CONCEPTS

3.1 Walk rate

Directional well is drilled along the plane A as shown in Figure 3-1(left). Coordinate XhYhZh is fixed in space, and the bit rotates around its own axis. Bit walk means bit has deviated from its original axis. If the bit does not walk at all or bit has a neutral tendency, the bit axis will remain in plane A. As shown in Figure 3-1(right), if the bit axis moves toward plane B, the bit walks left or the azimuth decreases. If the bit moves toward plane C, the bit walks right or azimuth increases. Walk rate tells how fast the bit has walked, and it is measured from the changes in azimuth over the certain interval.

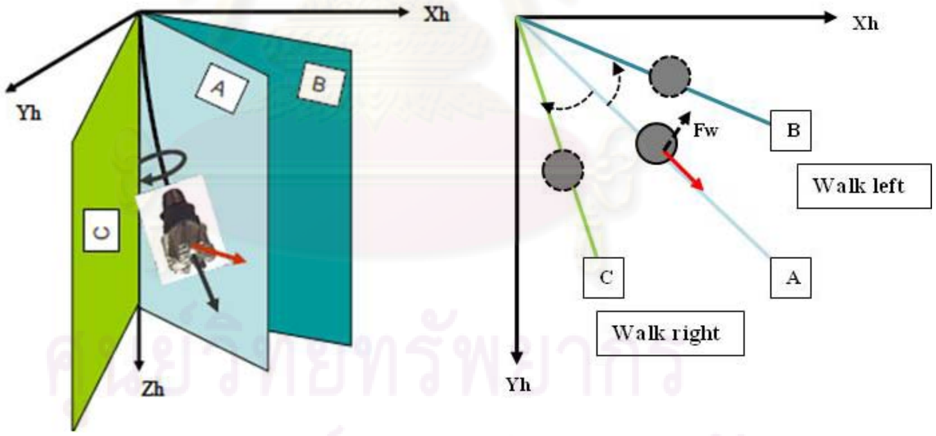


Figure 3-1: Bit walk definition (Chen S. *et al*., 2008)

Well inclination or hole angle is measured in degree deviated from the vertical axis, Zh, as shown in Figure 3-2(left). The vertical well has 0 degree inclination and the horizontal well has 90 degree inclination. Well direction is measured in degree azimuth as shown in Figure 3-2(right).

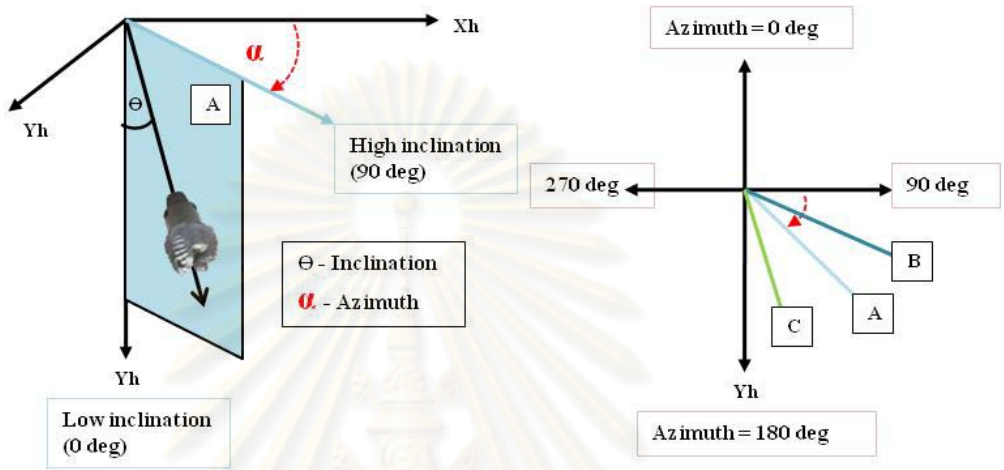


Figure 3-2: Inclination and azimuth

From Chen S. et al. (2008), the bit walks over the certain interval because there is the force, Fw, acting on a particular side of the bit and pushing it into that direction, shown in Figure 3-1(right). The amplitude and direction of this walk force, Fw, is characterized from bit model, BHA configuration, and a drillstring up to the surface rotating at certain RPM in a particular well profile with certain weight on bit (WOB) and drilling/interacting with that formation. In addition, the wellbore might not be in gauge along the well path and the bit might not rotate with constant RPM and WOB. There is no measurement tool that can be used to measure this walk force while drilling.

3.2 Factors affecting bit walk

From literature survey factors affecting bit walk of the rotary BHA included bit model, BHA configurations, formation characteristics, hole angle and curvature and drilling parameters. The studies were performed using actual field data observation and analysis, or three-dimensional computer model.

3.2.1 Bit model

Bit model has always been addressed as the major factor that influences bit walk. There were studies on how bit profile, number of gauge cutters and bit gauge length had effect the walk tendency.

From actual field data observation and analysis of Perry (1986) using 206 bit run data of 8-1/2” rotary BHA drilled in the Gulf of Thailand. There were 5 bit profiles used ranging from very flat to ballistic profile. Bit photos and details shown in Figure 3-3 and Table 3-1. The average walk rates per bit run were collected and summarized as shown in Table 3-2.

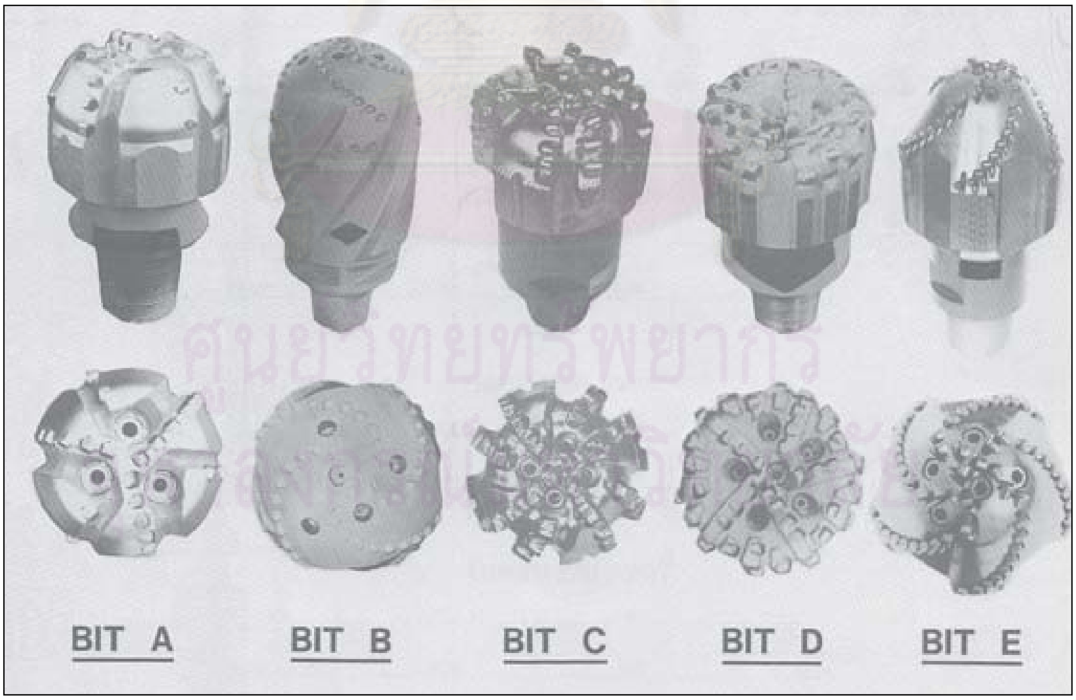


Figure 3-3: Five 8-1/2” PDC bits used in Perry study (Perry, 1986)

Table 3-1: Five 8-1/2” PDC bits used in Perry study (Perry, 1986)

Bit	Body Type	Total no. cutters	No. gauge cutters	Length of gauge (in.)
A	Steel	24	6	2.5
B	Steel	37	16	6.0
C	Matrix	36	9	3.0
D	Steel	41	5	3.0
E	Steel	42	10	3.3

Table 3-2: Result from Perry study (Perry, 1986)

Bit Type	A	B	C	D	E
Walk rate (deg/100ft)	0.14L	0.24L	0.08L	0.40R	0.37L
No. of bits	85	13	3	75	32
ROP (ft/h)	72	54	71	46	48
Footage	2473	1972	3017	2238	1814
WOB (klbs)	5 - 12	10 - 15	10 - 14	8 - 20	5 - 15
RPM	200 - 220	170 - 220	180 - 220	180 - 220	170 - 220

From the results, Bit D had the most right hand walk, 0.40 deg/100ft, and had a relatively flat profile comparing with other bits. Perry concluded that the bit with flat profile gave more right hand walk tendency than ones having ballistic profile. He also concluded that bit walk tendency was not affected by bit gauge length.

Menand, *et. al*, (2002) had developed a three-dimensional computer model that considered bit/formation interaction. The model could calculate the bit walk angle which could be translated to bit walk tendency as shown in Figure 3-4.

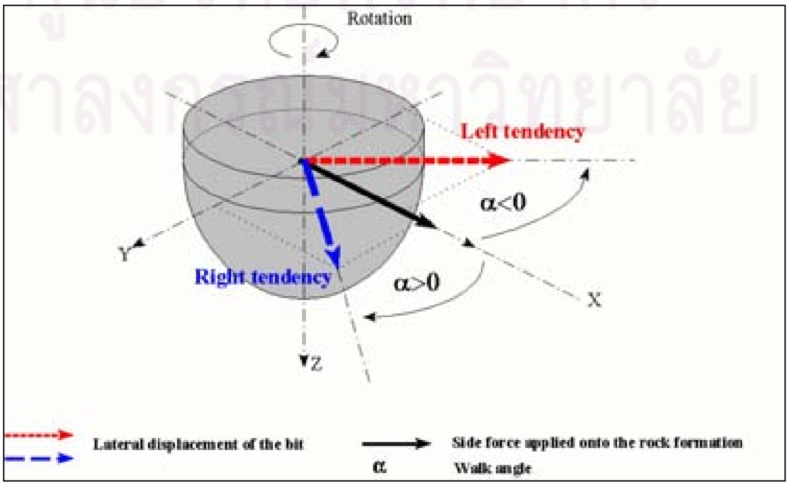


Figure 3-4: Definition of bit walk angle (Menand, *et. al*, 2002)

If the bit walk angle is more than zero degree, it has the right hand walk tendency and if the bit walk angle is less than zero degree, it has the left hand walk tendency. This three-dimensional computer model had been validated using the drilling bench, which enabling to test drill bit under simulated downhole conditions and to measure the bit walk angle.

The effect of bit walk rate from bit profile and bit gauge length was studied by testing three different PDC bit profiles with five different configurations as shown in Figure 3-5 and Figure 3-6. Bit gauge length was divided into active gauge length and passive gauge length as shown in Figure 3-6.

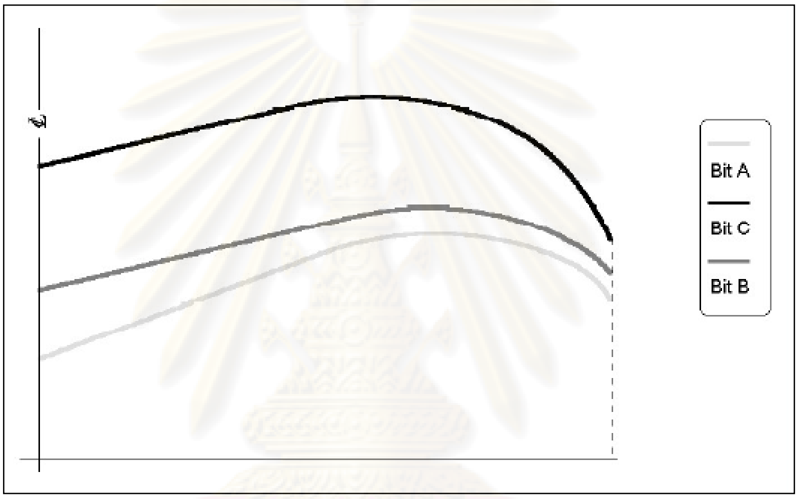


Figure 3-5: The three bit profiles of tested PDC bits (Menand, *et. al*, 2002)

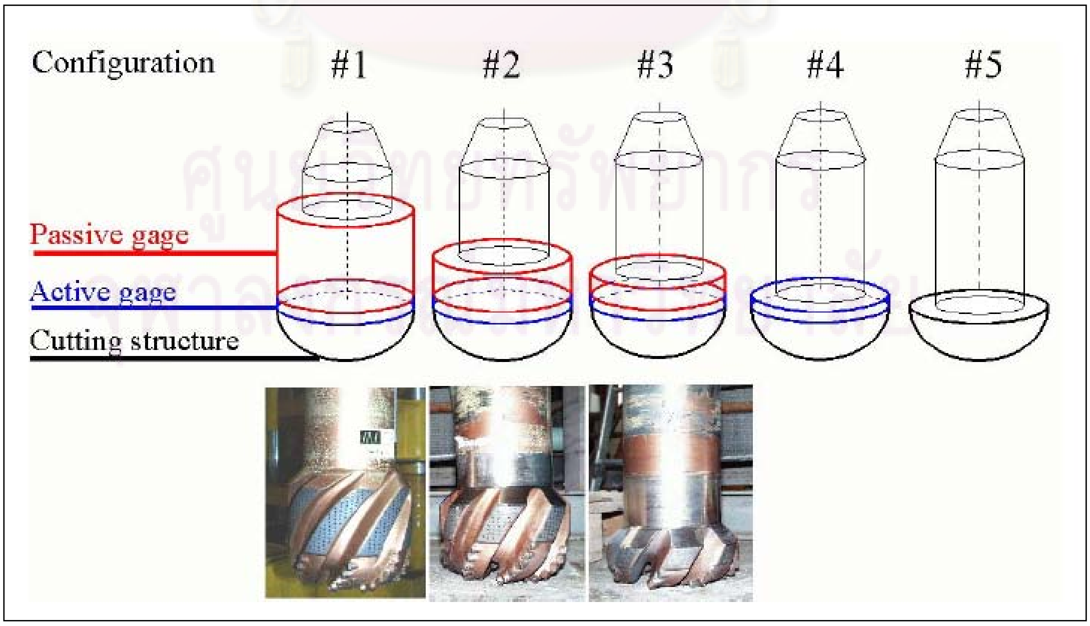


Figure 3-6: The five configurations to test bit gauge length (Menand, *et. al*, 2002)

The results from both three-dimensional computer model and from drilling bench showed that increasing bit gauge length resulting in increasing the left tendency, and when testing the bit profile with no bit gauge length, configuration#5, Bit-A demonstrated a right tendency, the Bit-C a left tendency and Bit-B a neutral tendency.

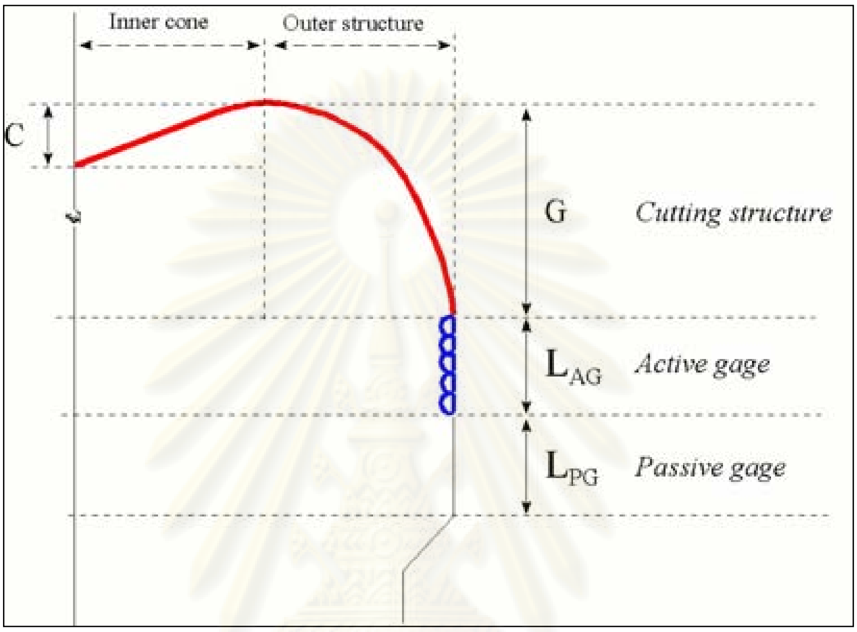


Figure 3-7: Description of PDC bit profile and gauge length (Menand, *et. al*, 2002)

From the test results, Menand found that the walk angle is then a function of the inner cone depth C and the outer structure height G and can be calculated simply using Equation 3-1.

$$\alpha = \arctan \frac{2(C-G)}{\tan(\omega_c+\theta_f)\ (C+G)} \tag{3-1}$$

C and G are inner cone depth and outer structure height as shown in Figure 3-7. ω_c is the angle of cutters and θ_f is the friction angle between PDC cutter and the rock.

The studies from Perry (1986) and Menand, *et. al*, (2002) can be summarized that bit model has an effect on bit walk rate. Bit with Ballistic profile gives more left tendency then the bit with flat profile, and a longer the bit gauge length gives more left tendency.

3.2.2 BHA configuration

Bottom Hole Assembly or BHA is the drilling equipments below the drillpipe down to the bit. Its primary function is to provide the weight to the bit to be able to make a hole. Over the years, the BHA has grown from one or two simple drill collars to quite a complex array of tools around 500 ft to 1,000 ft. The BHA will be designed to be able to follow the wellplan, hit the targets with optimum ROP.

BHA has also been addressed as another major factor that influences bit walk. BHA configuration including what drilling equipments added in the BHA, their placements in the BHA, and the shape, size, weight and stiffness of each component, affects the BHA behavior. The effects of location, size, shape, and properties of the BHA components on bit walk rate can be analyzed by available BHA models (Walker, 1986), however it will be specific to the particular BHA configuration, well profile and formation interaction which vary from case to case.

3.2.3 Hole angle and curvature

The hole angle, curvature of the borehole and wellbore enlargement can cause the BHA to be deflected in a complex shape nearly independent of the BHA components (Walker, 1986). Maldla and Sampaio (1989) had proposed a general rock-bit interaction model verified by field data indicating an inverse relationship between hole angle and walk rate as shown in Equation 3-2. From Maldla and Sampaio equation, well with higher hole angle has less bit walk rate.

$$K \propto \frac{Ib\ Ir}{\sin(\alpha)} \tag{3-2}$$

where

Ib = bit anisotropy

Ir = rock (formation) anisotropy

α = hole angle

K = walk rate

3.2.4 Formation characteristic

Ernst, Pastusek and Lutes (2007) concluded that the formation hardness has a significant effect on PDC bit steerability, as the formation hardness increases the ability of bit to drill laterally decreases and the bit walk rate also decreases.

Chen et.al (2008) presented effect of bit walk rate due to drilling the interbedded formation. They proposed another bit walk theory that the cutting force in the bit cone area gives the right walk tendency and the cutting force at the nose and shoulder area gives the left walk tendency. When drilling from soft to hard formation while building angle the nose and shoulder cutters cut in harder formation and therefore creates more force and pushes the bit to the left. On the other hand, if drilling form hard to soft formation the cone cutters cut the harder formation and therefore has more force in the cone area and pushes the bit to the right as shown in Figure 3-8.

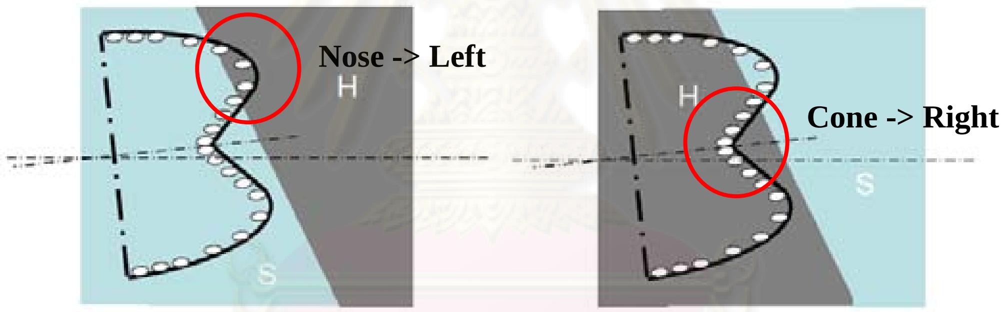


Figure 3-8: Bit walk due to formation transition (Chen et. al, 2008)

Formations with dipping bedding planes affects the borehole path, from the historical data bit generally tends to drill updip when the bedding planes have dips of less than 45 deg, and tends to drill downdip when bedding dips are greater than 60 deg (Walker, 1986).

The effect of walk rate due to formation characteristics can be summarized that harder formation decreases the bit walk rate. Bit tends to walk left when drilling from soft to hard formation and tends to walk right when drilling hard to soft formation. And formation dip and strike has effect on the bit walk tendency.

3.2.5 Drilling parameter

The parameters that we can control at surface when drilling a well are mud flow rate, mud properties, rotational speed (RPM) and weight on bit (WOB). RPM and WOB are the two parameters that we frequency adjust to optimize the drilling rate and well directional. The drilling rate or rate of penetration is depended on the amount of rock has removed in a period of time which is directly result from WOB and RPM.

According to Ernst, Pastusek and Lutes (2007), WOB is widely used to increase the turn rate under certain drilling conditions. This is a result from increasing the penetration rate and the bit tilt. Effect of bit walk from drilling parameters has been investigated using the computer model to simulate the bit tilt and side loading that induced by a BHA inside the wellbore. The tests performed using the same bit design to drill the medium hard Bedford (Indiana) Limestone then lateral displacements and vertical depth were recorded. The test result was shown in Figure 3-9. WOB (represented by ROP) and RPM were varied, and the side cutting angle representing the walk rate was recorded. The results showed that at a constant RPM, side cutting angle decreased when ROP increased. While at a constant ROP, lower RPM exhibits higher side cutting angle. From the result, it could be concluded that WOB and RPM exhibited an inverse relationship with the walk rate, or walk rate decreased when WOB and RPM increased.

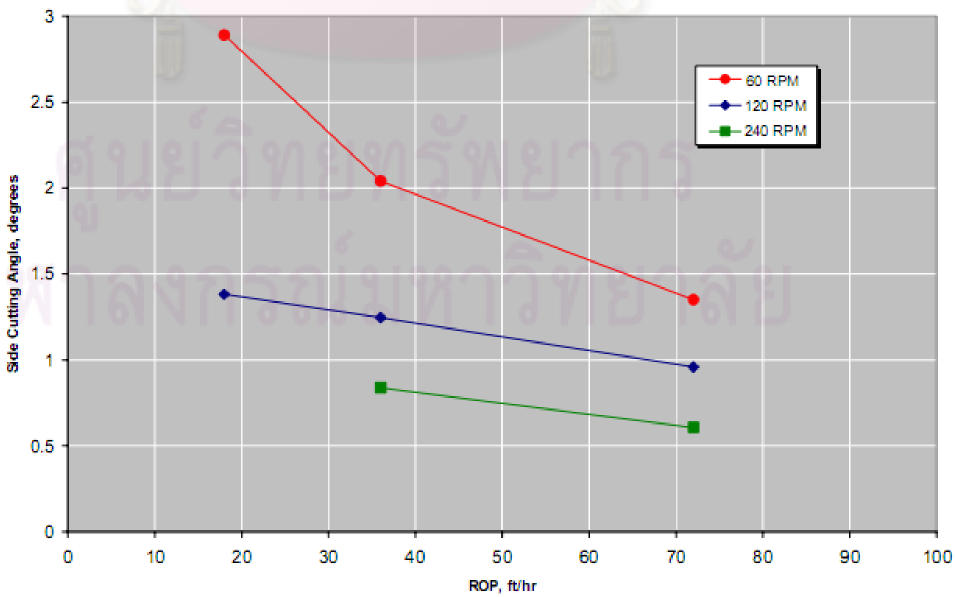


Figure 3-9: Side cutting angle (walk rate) vs. operating parameters (WOB, RPM)
(Ernst, Pastusek and Lutes, 2007)

3.3 Thailand drilling operation

3.3.1 Well profile

Petroleum wells are drilled in the Gulf of Thailand around 300-500 wells per year. The typical well schematic and the well profile are shown in Table 3-3 and Figure 3-10. The well is drilled in 3 sections; top hole in 12-1/4", intermediate hole in 8-1/2" and reservoir section in 6-1/8". The well profile in reservoir section is a holding tangent as seen in blue/green color line in Figure 3-10.

Table 3-3: Well schematic in the Gulf of Thailand

Hole Size	Bit	MD (ft)	TVD (ft)	ROP (ft/h)	Comment
12-1/4"	Digger bit	900	900	350	Vertical or slight build angle
8-1/2"	PDC bit (4 blade 19mm cutter)	6500	4500	250-450	Initial build/turn, holding tangent then final drop/turn
6-1/8"	PDC bit (4 blade 16-19mm cutter)	10500	9000	100-180	Reservoir section, 30-50 deg hole inclination. Holding tangent with slight build/drop

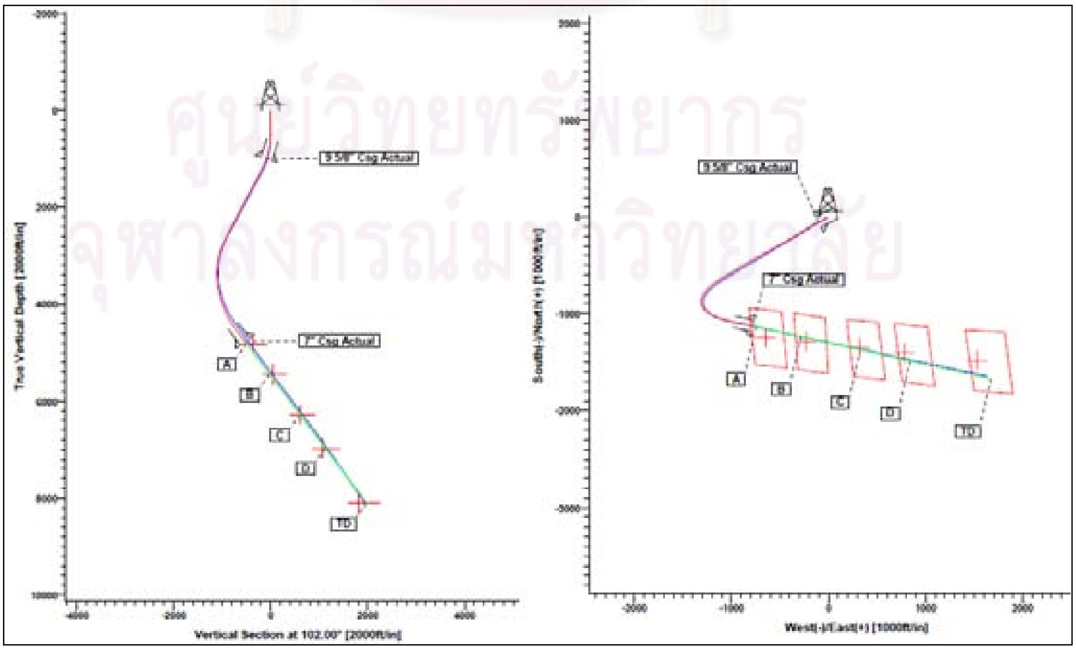


Figure 3-10: Well profile in the Gulf of Thailand

3.3.2 Bit and BHA of 6-1/8" section

Poly Crystalline Diamond (PDC) bit with 4 to 5 blades and 16 to 19mm cutter is generally used. Most of the well objective is to drill a section with a single bit run, hitting all targets with fast rate of penetration (ROP). Figure 3-11 showed the photo of 4 bladed 16mm cutter PDC bit that is normally used in the Gulf of Thailand.

Figure 3-11: 6-1/8" PDC bit used in the Gulf of Thailand

The typical BHA configuration for drilling the reservoir section is listed in Table 3-4. The second and third items, the near bit stabilizer outer diameter (OD) and the length of extension sub can be varied depending on well inclination and the build/drop rate required. For example near bit stabilizer OD can be decreased to 6-1/16" or 6" when high amount of drop angle required. And BHA with 0ft extension can build angle quickly but take longer time to drop angle contradict to the BHA with 2ft extension which can drop quickly but build slowly.

Another BHA component that plays important role in build/drop angle is the adjustable gauge stabilizer (AGS), as shown in Figure 3-12. This equipment is a hydraulically actuated integral blade stabilizer with three spiral blades. Each blade carries four pistons which are extended by the differential pressure between the inside the AGS collar and wellbore annulus. The pistons are retracted by a spring to the "at rest" position once the pumps are turned off. In order to activate the tool a pressure differential of 450 psi is required. This needs to be maintained for the tool to continue to function.

Table 3-4: BHA component of 6-1/8” section in the Gulf of Thailand

Item	Components	Length (ft)	Total Length (ft)	OD (in)	Maximum OD (in)
1	6-1/8" PDC bit	0.80	0.80	6.125	6.125
2	6-1/8" near bit stabilizer	2.45	3.25	5.000	6.125
3	2ft extension sub	2.00	5.25	5.000	5.000
4	Adjustable gauge stabilizer	10.51	15.76	4.790	5.625/6.125
5	Cross-over sub	1.98	17.74	4.750	5.000
6	MWD/LWD	33.93	51.67	4.750	4.750
7	6" stabilizer	5.70	57.37	5.180	5.958
8	4 x drill collar	123.90	181.27	4.750	4.750
9	Cross-over sub	2.76	184.03	4.000	4.813
10	24 x HWDP	738.02	922.05	4.000	4.875
11	Drill pipe			4.000	4.875

The pistons have the rest position and two operating positions; close and open. For 4-3/4” AGS used in drilling the 6-1/8” hole, the rest position is 1/8” below the surface of the stabilizer blade. The first operating position is flush with the stabilizer blade surface (close position, 5-5/8” OD) and the second is fully extended (open position, 6-1/8” OD).

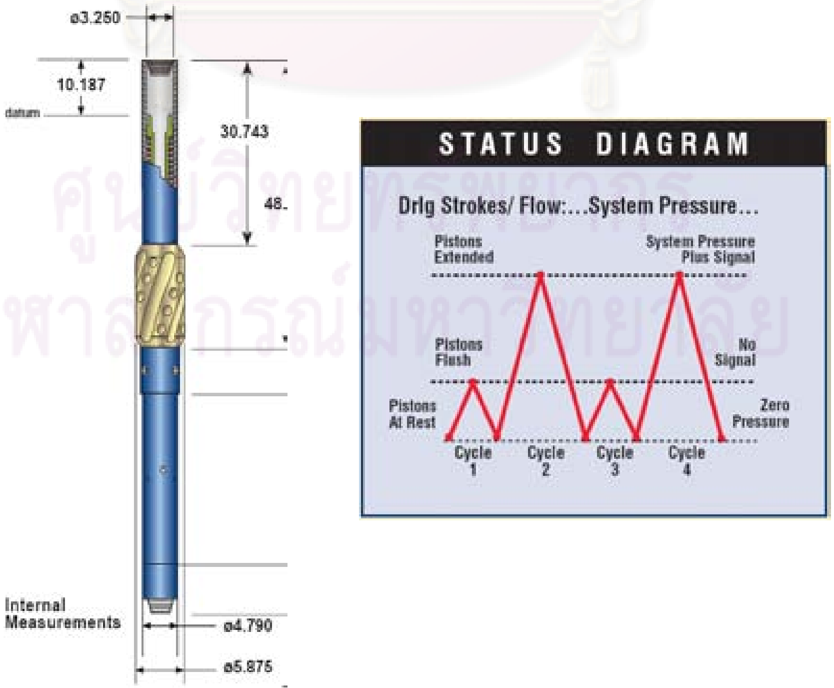


Figure 3-12: Adjustable gauge stabilizer

AGS can control the well inclination using fulcrum concept as shown in Figure 3-13. When the AGS opened the BHA will act as pendulum and has dropping tendency from the gravity, when the AGS closed BHA will fall on low side of the wellbore pushing the bit to tilt upward and build angle.

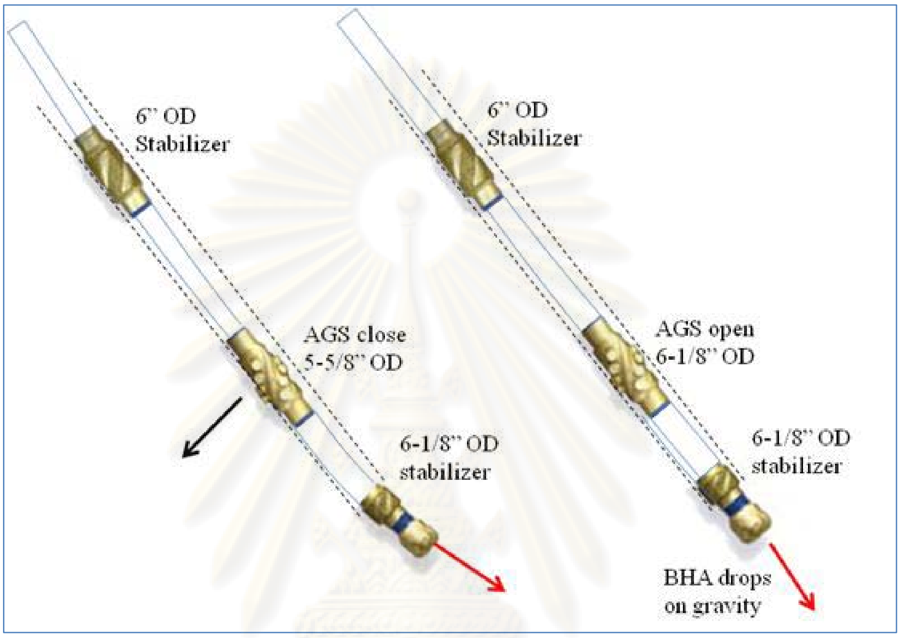


Figure 3-13: Adjustable gauge stabilizer in close and open position results in BHA building and dropping

3.3.3 Formation characteristic in the production section

The productive Miocene gas sands are in highly faulted sand/shale sequences which range in depth from 4,500 ft TVD to 9,000 ft TVD. The formation unconfined compressive strength ranges from 3 to 12 kpsi. Figure 3-14 showed petroleum wells drilled into small fault blocks. A high temperature gradient exists (4 degF/100ft), presenting mechanical difficulties at depth for downhole mud motor run.

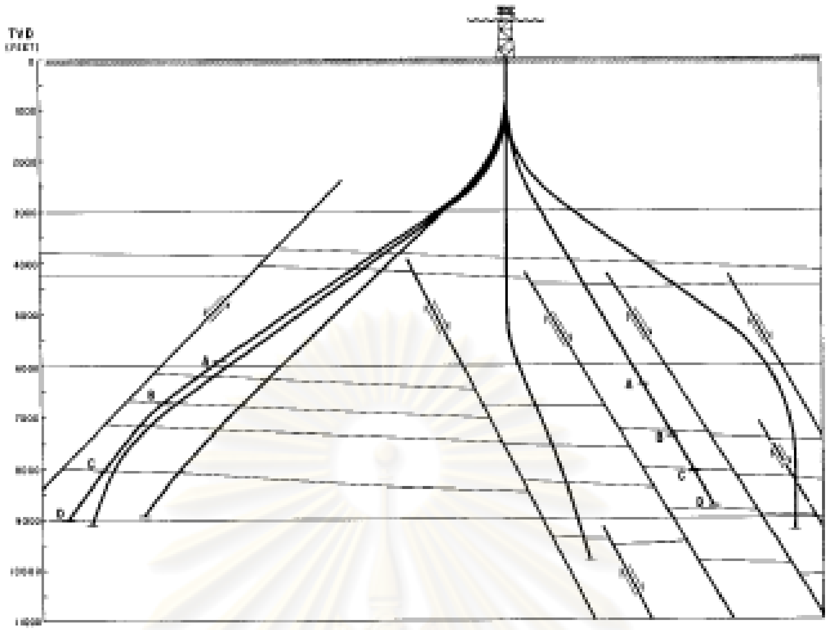


Figure 3-14: Petroleum wells in the Gulf of Thailand

CHAPTER IV
METHODOLOGY

This chapter was divided into six sections from Chapter 4.1 to 4.6. The first section in Chapter 4.1 presented the field data formatting that had been collected and compiled to use in this study. The second section described the parameters influencing the walk rate that included in this study. Each parameter was divided into groups and the relationships of each parameter and the walk rate were established using two methods, with and without constraints. When establishing the relationship of one parameter to the walk rate with constraints, other parameters will be fixed or limited into a small range in order to minimize the influence of other parameters to the walk rate. Establishing the relationship without constraints was presented in Chapter 4.3, and establishing the relationship with constraints was presented in Chapter 4.4. The results from Chapter 4.4 were used in creating the walk rate prediction table, showed in Chapter 4.5. In the last section, the created walk rate prediction table was validated using the actual field data from the well drilled after in year 2009. The methodology diagram of the walk study was shown in Figure 4-1.

When considering the parameters to be used in the study, the prior objective was to include as many parameters as possible, so that we could have more understand of what parameters and how each parameter affecting the bit walk in the Gulf of Thailand. However there is a limitation on availability of some data for example the formation dip and strike. Finally seven parameters were selected and analyzed including bit model, extension length, AGS setting, hole angle, TVD depth, WOB and RPM. The extension length and AGS setting were considered as the BHA configurations regarding to the stabilizer placement and size.

From three typical bit models and three BHA configurations that normally used in the Gulf of Thailand, there were total of 495 wells used for the study. When we drill a well, one bit model and one BHA configuration are used and cannot be changed unless we stop drilling and pull them out of hole. Unlike the AGS setting, hole angle, TVD depth, WOB, RPM including the walk rate that their values can be changed while drilling. However, the azimuth data that used for calculating the walk rate is only measured every 100ft. The study therefore considered each survey station as one data point and there were total of 17,625 data points from 495 wells used in this study.

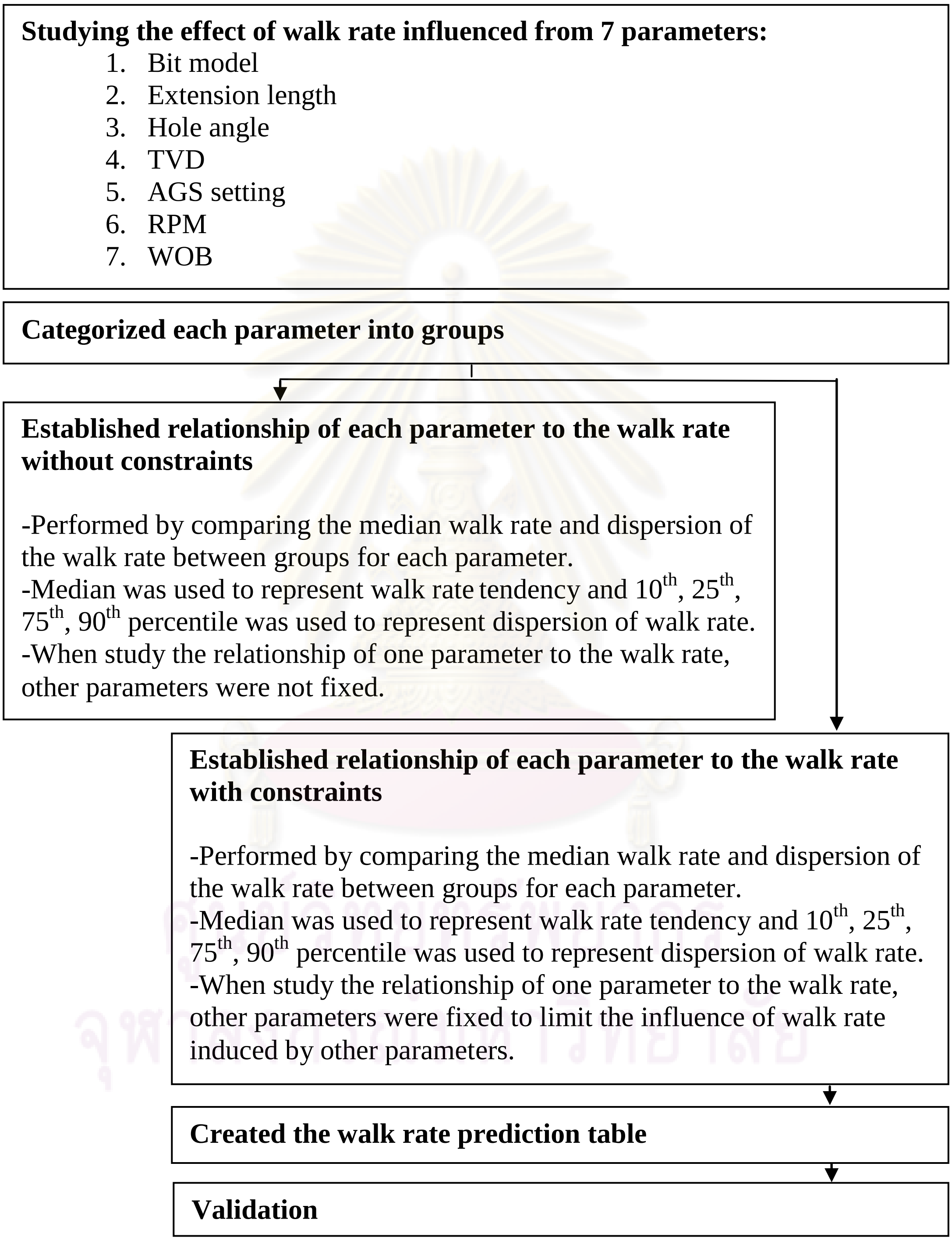


Figure 4-1: Methodology diagram of the walk rate study

4.1 Field data used for the study

When drilling petroleum well the 100ft-drillpipes will be added continuously and the directional survey will then be taken every 100ft. We therefore have the directional survey data including the measured depth, hole angle and azimuth every 100ft interval.

The TVD data can be calculated from directional survey data. The average surface drilling parameters over 100ft are collected, together with the AGS setting. One data point for this study was therefore composed of the directional survey data, the surface drilling parameters, the AGS setting, bit model and BHA configuration used. Table 4-1 showed an example of the data from one selected well and one line was equal to one data point. Table 4-2 presented how the average walk rate for each survey station or each data point was calculated. The average walk rate can be calculated using the azimuth and the measured depth.

This study used actual field data from 495 wells drilled from year 2006 to year 2008 that used three interested bit model and three BHA configurations and there are total of 17,625 data points.

Table 4-1: Measured parameters and directional survey data of 6-1/8” of selected well

Bit Model	Bit-A						
BHA Configurations	BHA with 2ft extension						
Directional survey data				Output	Surface drilling data		
Measured depth (ft)	TVD depth (ft)	Hole angle (deg)	Azimuth (deg)	walk rate (deg/100ft)	WOB (klbs)	RPM	AGS Setting
9229	5572	34.4	96.9	0.000	10	200	Open
9326	5652	34.7	96.7	-0.186	10	200	Close
9421	5730	34.7	96.9	0.189	10	200	Open
9517	5808	35.0	96.7	-0.188	10	200	Close
9612	5886	35.4	96.7	0.000	10	200	Close
9707	5963	35.3	96.6	-0.179	10	200	Open
9802	6041	35.5	96.6	0.000	10	200	Close
:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:
12765	8460	34.4	85.5	-0.729	12	200	Close
12955	8618	33.6	84.4	-0.558	12	200	Close
13049	8696	33.4	84.0	-0.372	12	200	Close
13144	8775	33.0	84.0	0.000	12	200	Close
13335	8936	33.0	83.2	-0.461	12	200	Close
13525	9095	32.4	82.1	-0.558	12	200	Close
13664	9212	33.7	81.9	-0.129	12	180	Close

Table 4-2: Walk rate calculation

Bit Model	Bit-A			
BHA Configurations	BHA with 2ft extension			
Measured depth (ft)	TVD depth (ft)	Hole angle (deg)	Azimuth (deg)	walk rate (deg/100ft)
13525	9095	32.4	82.1	
13664	9212	33.7	81.9	$= \frac{(81.9 - 82.10)}{(13664 - 13525)} * 100 = -0.129$

4.2 Parameters affecting walk rate used for the study

There were seven parameters used in this study including; bit model, extension length, AGS setting, hole angle, TVD depth, WOB and RPM. The extension length and AGS setting were considered as the BHA configurations regarding to the stabilizer placement and size. Each parameter was categorized into groups therefore the walk rate between groups could be compared, as shown in Table 4-3. The group intervals were selected to match the drilling operation and to be practical for using as the guideline for pre-job planning.

Table 4-3: Parameters used for walk rate study

No.	Parameters	Group1	Group2	Group3
1	Bit model	Bit-A	Bit-B	Bit-C
2	Extension (ft)	0ft	1ft	2ft
3	Hole angle (deg)	< 30	30-40	>40
4	TVD depth (ft)	5000 - 7000	> 7000	
5	AGS setting	close	open	
6	RPM	< 180	180 - 200	> 200
7	WOB	< 11 klbs	11-13 klbs	> 13 klbs

4.2.1 Bit model

Four bladed 16-19mm cutter PDC bit models; Bit-A, Bit-B and Bit-C were used in this study. These three bit models had different cutting structures or different cutter layouts. Bit description and number of bits used in the study has shown in Table 4-4 and the bit photo has shown in Figure 4-2.

Table 4-4: Three bit model used in the study

bit model	Bit-A	Bit-B	Bit-C
bit type	PDC bit	PDC bit	PDC bit
number of blade	4 blade	4 blade	4 blade
cutter size	19mm	16mm	16mm
number of cutter	23 cutters	29 cutters	28 cutters
data: number of bits	168 bits	213 bits	114 bits
data: number of data points	6,126	7,532	3,967

Figure 4-2: Three bit model used in the study

4.2.2 Extension length

Three Rotary BHA configurations that widely used in Gulf of Thailand were selected to use in this study including BHA with no extension, 1ft extension and 2ft extension. These BHAs had different extension lengths between the near bit stabilizer and the adjustable gauge stabilizer as shown in Table 4-5. Varying extension lengths caused BHA to have different stabilizer placements. As shown in Figure 4-3, the distances of the stabilizer blade center between the 6-1/8" near bit stabilizer and the adjustable gauge stabilizer were 7.4ft, 8.4ft and 9.4ft corresponding to the 0ft, 1ft and 2ft extension respectively.

Table 4-5: BHA with 0ft, 1ft and 2ft extension

BHA with 0ft extension	BHA with 1ft extension	BHA with 2ft extension
bit	bit	bit
6-1/8" near bit stabilizer	6-1/8" near bit stabilizer	6-1/8" near bit stabilizer
no extension sub	**1 foot extension sub**	**2 feet extension sub**
adjustable gauge stabilizer	adjustable gauge stabilizer	adjustable gauge stabilizer
cross-over sub	cross-over sub	cross-over sub
MWD/LWD	MWD/LWD	MWD/LWD
6" stabilizer	6" stabilizer	6" stabilizer
drill collar	drill collar	drill collar
cross-over sub	cross-over sub	cross-over sub
HWDP	HWDP	HWDP

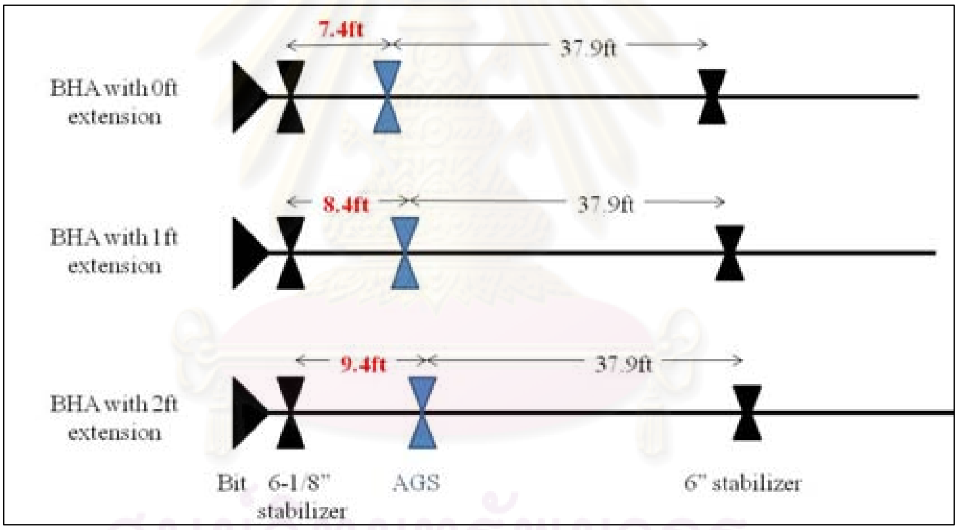


Figure 4-3: BHA with 0ft, 1ft and 2ft extension

Number runs of Bit-A, Bit-B and Bit-C that using these three BHAs (0ft, 1ft and 2ft extension) were shown in Table 4-6. The quickly build angle BHA or the BHA with 0ft extension was not used as many as BHA with 1ft and 2ft extension.

Table 4-6: Number of runs and data points of BHA with 0ft, 1ft and 2ft extension

Extension length	0ft extension	1ft extension	2ft extension	Total
data: number of runs	54 runs	217 runs	224 runs	495 runs
data: number of data points	1,469	7,958	8,198	17,625

With three bit models and three BHA configurations gave nine different bit/BHA configurations as seen in Table 4-7. This thesis paper will termed these “9 bit/BHA configurations” as “9 BHA configurations”. The number of runs and data points of each BHA configurations was also shown in Table 4-8.

Table 4-7: Nine bit/BHA configurations or nine BHA configurations

Extension length / Bit model	**Bit-A**	**Bit-B**	**Bit-C**
0ft extension	BHA-1 (Bit-A with 0ft extension)	BHA-2 (Bit-A with 1ft extension)	BHA-3 (Bit-A with 2ft extension)
1ft extension	BHA-4 (Bit-B with 0ft extension)	BHA-5 (Bit-B with 1ft extension)	BHA-6 (Bit-B with 2ft extension)
2ft extension	BHA-7 (Bit-C with 0ft extension)	BHA-8 (Bit-C with 1ft extension)	BHA-9 (Bit-C with 2ft extension)

Table 4-8: Number of runs and data points of nine BHA configurations

Extension length / Bit model	**Bit-A**	**Bit-B**	**Bit-C**	**Total**
0ft extension	18 runs (647 data points)	21 runs (462 data points)	15 runs (360 data points)	54 runs (1,469 data points)
1ft extension	89 runs (3,290 data points)	76 runs (2,685 data points)	52 runs (1,983 data points)	217 runs (7,958 data points)
2ft extension	61 runs (2,189 data points)	116 runs (4,385 data points)	47 runs (1,624 data points)	224 runs (8,198 data points)
Total	168 runs (6,126 data points)	213 runs 7,532 data points)	114 runs (3,967 data points)	495 runs (17,625 data points)

4.2.3 Hole angle

Well profile is designed to be tangent with no or small change in hole angle due to the limit used of mud motor. The frequency plot of the hole angle using 17,625 data points from 495 runs was presented in Figure 4-4. In this study, the hole angle was grouped into 3 groups including 1) hole angle < 30 deg, 2) 30 deg ≤ hole angle ≥ 40 deg and 3) hole angle > 40 deg. These groups were divided followed the actual Thailand drilling operation. Well profile is normally planned with hole angle > 30 deg, and the BHA with 2ft extension are normally used when hole angle > 40 deg because it has a quick dropping tendency. The number of data points of each hole angle's group was shown in Table 4-9.

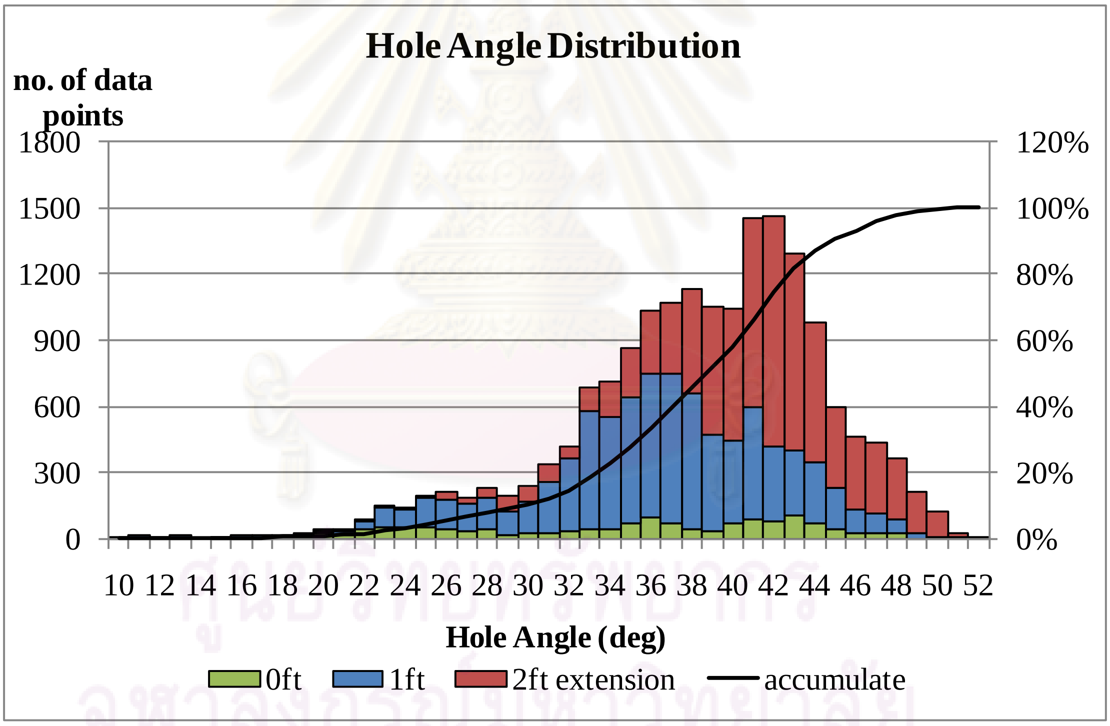


Figure 4-4: Hole angle distribution using 17,625 data points from 495 runs

Table 4-9: Number of data points of each group of hole angle

Hole angle	< 30 deg	30 - 40 deg	> 40 deg	Total
data: number of data points	1,603	7,648	8,374	17,625

4.2.4 TVD depth

From chapter 2, the concept and theory, the walk rate influenced by formation characteristics including formation strength, formation anitrosopy and formation dip and strike.

For the Gulf of Thailand, the formation is composed of the alternating shale and sand intervals with unconfined compressive strength ranging 3-12 kpsi. The unconfined compressive strength or the formation strength increases when TVD increases as shown in Figure 4-5. The TVD depth was then used to represent the formation strength in this study. The green and yellow color in lithology column represented shale and sand respectively.

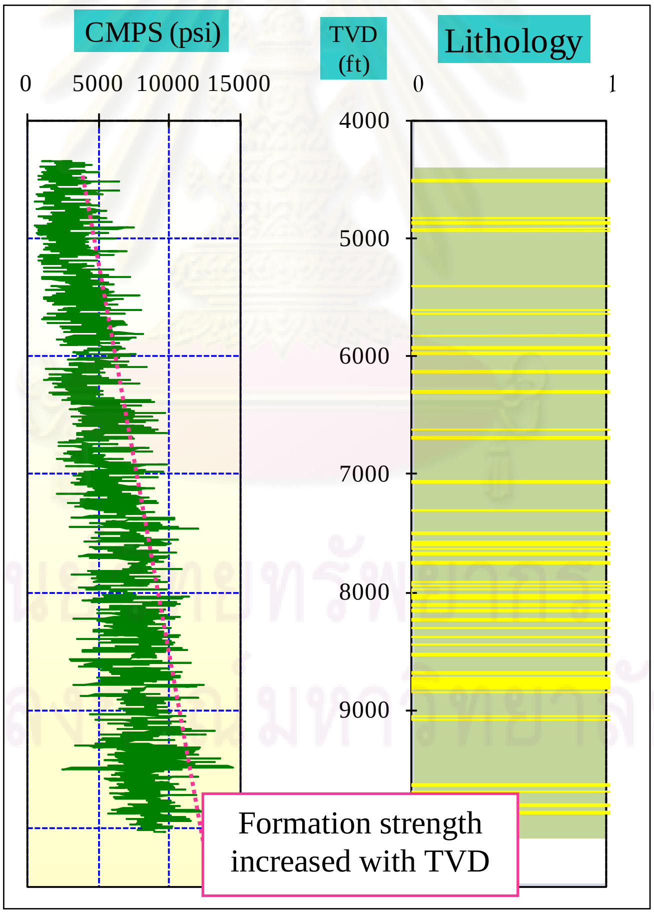


Figure 4-5: Formation strength and lithology of a selected well

In this study, the TVD depth was grouped into 2 groups including 1) TVD from 5,000 to 7,000ft and 2) TVD more than 7,000ft. There was the change in formation from TVD Group-1 to TVD Group-2, as shown in Figure 4-6, the formation has changed from red shale to grey shale. TVD Group-2 had higher formation strength than TVD Group-1. The number of data points of each TVD group was also shown in Table 4-10.

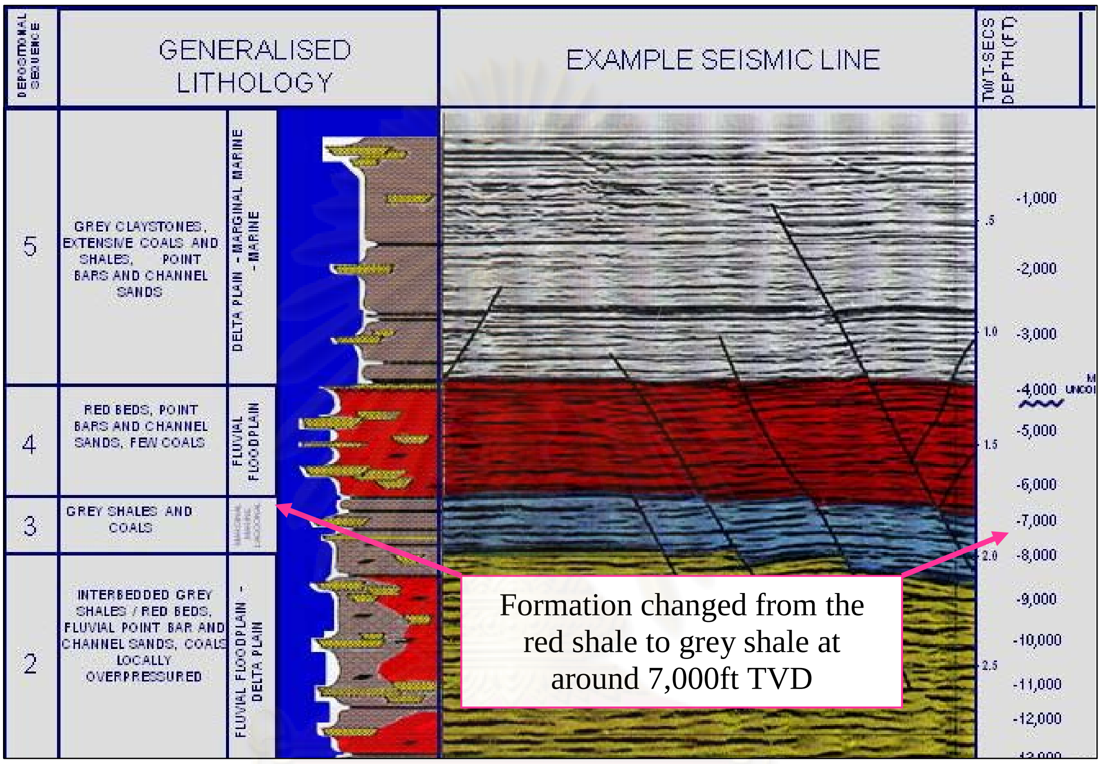


Figure 4-6: Lithology in the Gulf of Thailand

Table 4-10: Number of data points of each TVD group

TVD depth	**5,000 - 7,000 ft**	**> 7,000 ft**	**Total**
data: number of data points	7,841	8,562	16,403

4.2.5 AGS setting

AGS can be set into close and open position by cycling the mud pump. Changing the AGS setting caused BHA to have a different stabilizer OD or a different BHA configuration. Two BHA configurations resulted from change the AGS setting was shown in Table 4-11 and Figure 4-7. The effect of changing the AGS setting was stated in Chapter 3.3, Thailand drilling operation. The number of data points of each AGS setting was also shown in Table 4-12.

Table 4-11: BHA with two AGS setting; close and open

BHA with AGS close	BHA with AGS open
bit	bit
6-1/8" near bit stabilizer	6-1/8" near bit stabilizer
extension sub	extension sub
5-5/8" AGS stabilizer	6-1/8" AGS stabilizer
cross-over sub	cross-over sub
MWD/LWD	MWD/LWD
6" stabilizer	6" stabilizer
drill collar	drill collar
cross-over sub	cross-over sub
HWDP	HWDP

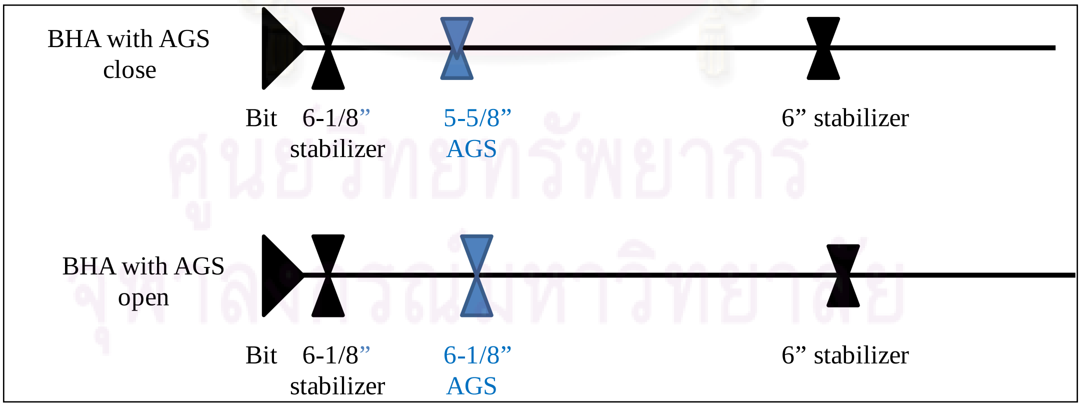


Figure 4-7: BHA with two AGS setting; close and open

Table 4-12: The number of data points of each AGS setting

AGS setting	close	open	Total
data: number of data points	7,401	10,224	17,625

4.2.6 RPM

For slimhole drilling in the Gulf of Thailand, the drill string is normally rotated from 120 to 240 RPM. The RPM frequency plot using 17,625 data points from 495 runs was presented in Figure 4-8. In this study, the RPM was grouped into 3 groups including 1) RPM < 180, 2) 180 ≤ RPM ≥ 200 deg, and 3) RPM > 200. These groups were divided to be practical when use as a guideline for RPM recommendation.

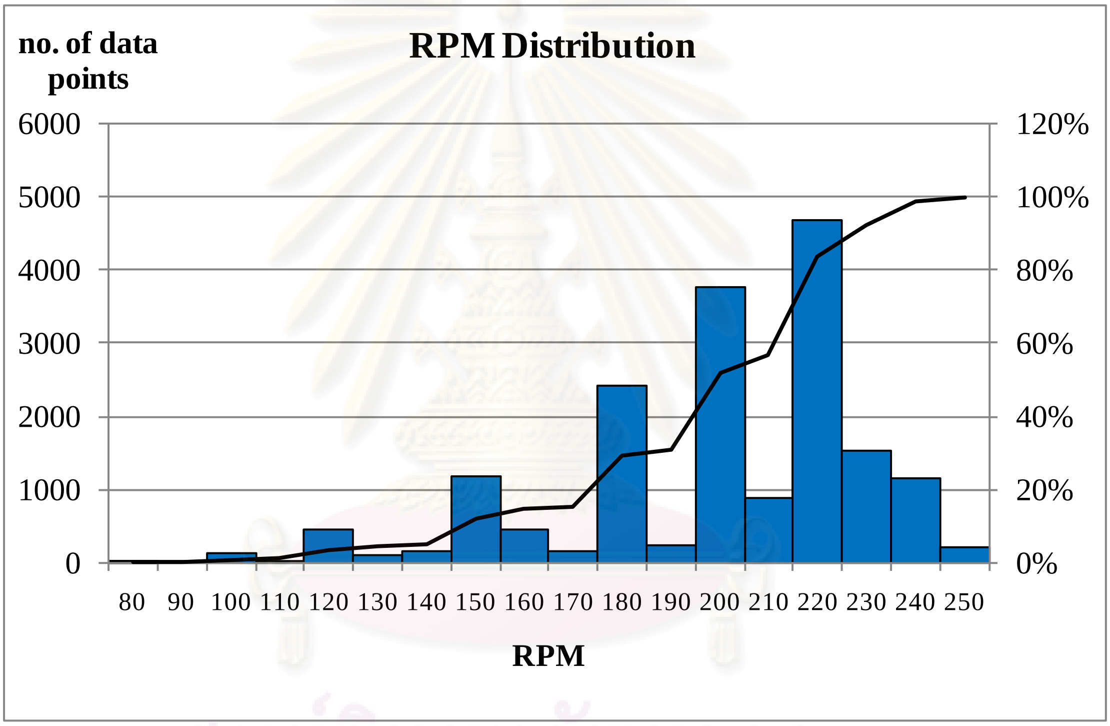


Figure 4-8: RPM distribution using 17,625 data points from 495 runs

4.2.7 WOB

The weight on bit (WOB) is normally applied from 8 to 14 klbs. The WOB frequency plot using 17,625 data points from 495 runs was presented in Figure 4-9. In this study, the WOB was grouped into 3 groups including 1) WOB < 11 klbs, 2) 11 klbs ≤ WOB ≥ 13 klbs and 3) WOB > 13 klbs. These groups were divided to be practical when use as a guideline for WOB recommendation. The number of data points of each group of RPM and WOB was also shown in Table 4-13.

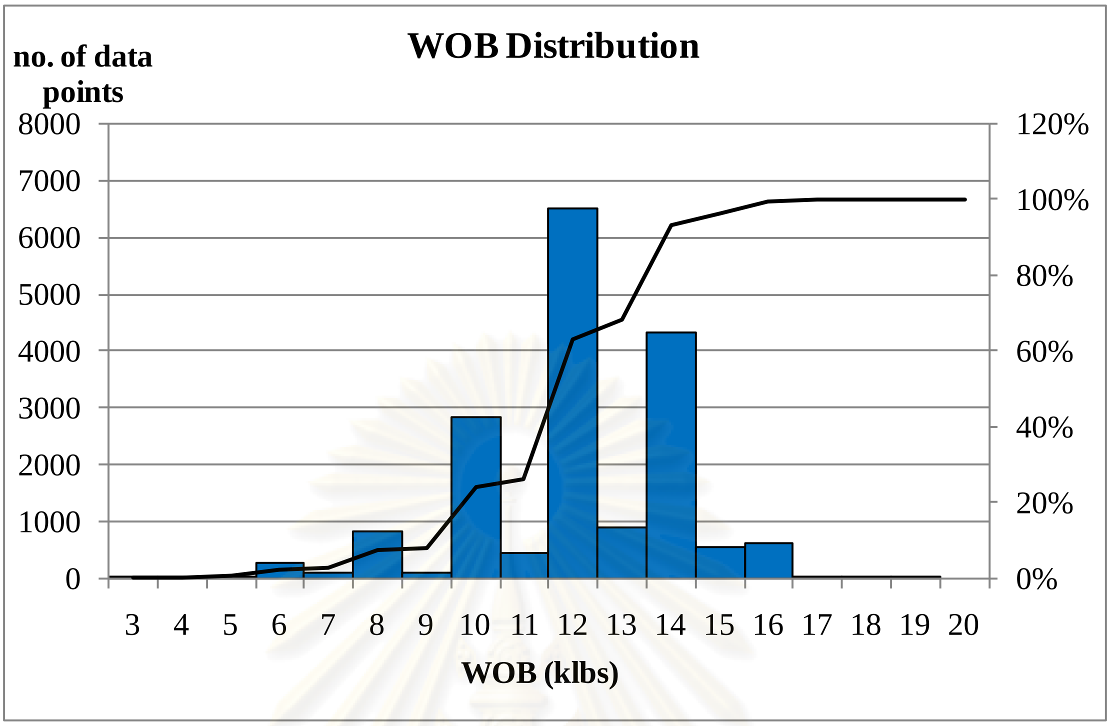


Figure 4-9: WOB distribution using 17,625 data points from 495 runs

Table 4-13: The number of data points for each group of RPM and WOB

RPM	**< 180 RPM**	**180 - 200**	**> 200 RPM**	**Total**
data: number of data points	2,733	6,383	8,509	17,625

WOB	**< 11 klbs**	**11 -13 klbs**	**> 13 kbls**	**Total**
data: number of data points	4,219	7,844	5,562	17,625

4.3 Established relationship of each parameter to the walk rate without constraints

Each parameter was plotted against the walk rate to find if there was a relationship between the parameter and the walk rate. Walk rate value was plotted on scatter plot and also presented using the median and 10th, 25th, 75th, 90th percentile (P10, P25, P75 and P90) to define its tendency and its dispersion. Median was selected to represent the walk rate tendency because we were coping with a large amount of repeated values and our objective was to predict the walk rate, therefore the median was more suitable to use. The relationships of each parameter to the walk rate were summarized in Section 4.3.8.

Figure 4-10 showed example of median walk rate and P10, P25, P75 and P90 of Bit-A. The median walk rate of Bit-A (from 6,126 data points) was equal to 0 deg/100ft and the P10, P25, P75 and P90 was equal to -0.52, -0.21, 0.11 and 0.32 deg/100ft respectively.

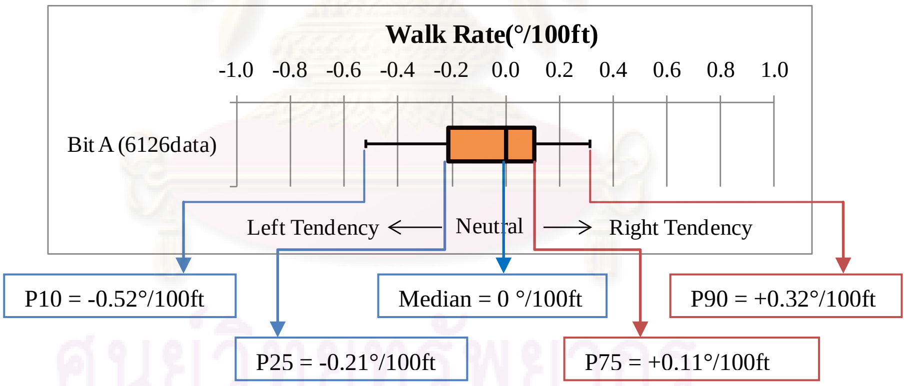


Figure 4-10: Median walk rate and 10th, 25th, 75th, 90th percentile of Bit-A

4.3.1 Bit model vs. walk rate

Walk rate and bit model data point was plotted on scatter plot as shown in Figure 4-11(Top). Each dot color represented each bit model and amount of data points also shown on the vertical axis and on the label. Walk rate data for each bit model also presented with median and P10, P25, P75 and P90 as shown in Figure 4-11 (Bottom).

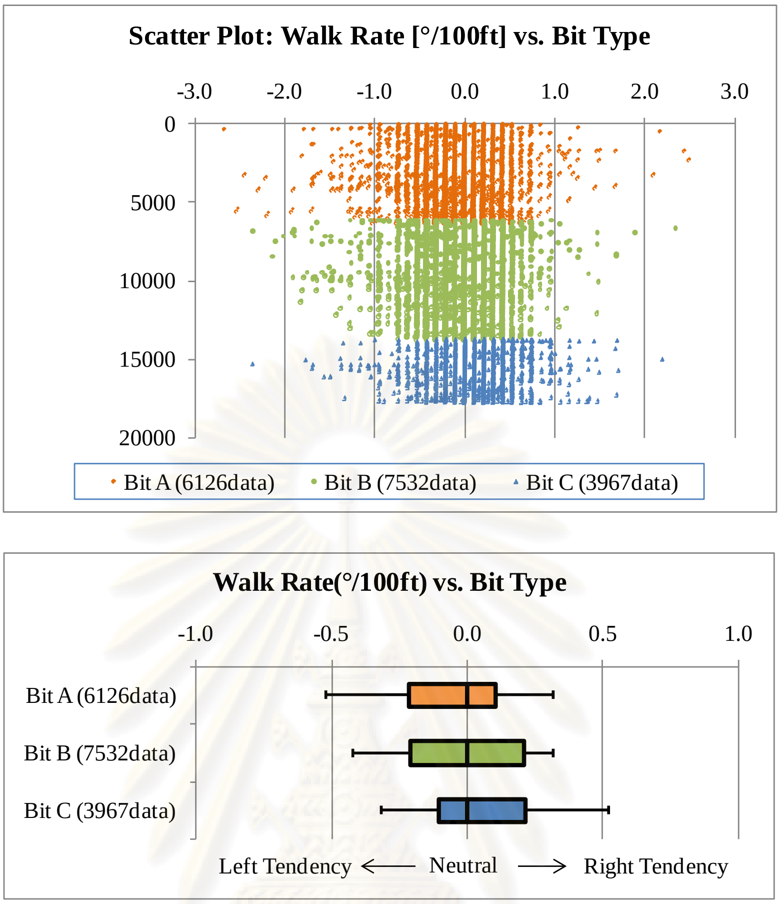


Figure 4-11: Relationship of bit model vs. walk rate in scatter plot and percentile

From Figure 4-11, Bit-A had median walk rate of 0.00 deg/100ft and had P10, P25, P75 and P90 equal to -0.52, -0.21, 0.11 and 0.32 deg/100ft respectively. Bit-B had median walk rate of 0.00 deg/100ft and had P10, P25, P75 and P90 equal to -0.42, -0.21, 0.21 and 0.32 deg/100ft respectively. Bit-C had median walk rate of 0.00 deg/100ft and had P10, P25, P75 and P90 equal to -0.32, -0.11, 0.21 and 0.52 deg/100ft respectively. Every bit model had median walk rate equal to 0 deg/100ft, however by comparing the walk rate using the P25 and P75, Bit-A, Bit-B and Bit-C had tendency to walk left, neutral and right respectively.

It could be concluded by comparing the walk rate value of each bit model that the walk rate was affected by bit model and Bit-A, Bit-B and Bit-C had tendency to walk left, neutral and right respectively.

4.3.2 Extension length vs. walk rate

Walk rate and extension length data point was plotted on scatter plot as shown in Figure 4-12(Top). Three dot colors represented BHA with 0ft, 1ft and 2ft extension. The amount of data points was shown in the vertical axis and on the label. Walk rate data for each extension length also presented with median and P10, P25, P75 and P90 as shown in Figure 4-12 (Bottom).

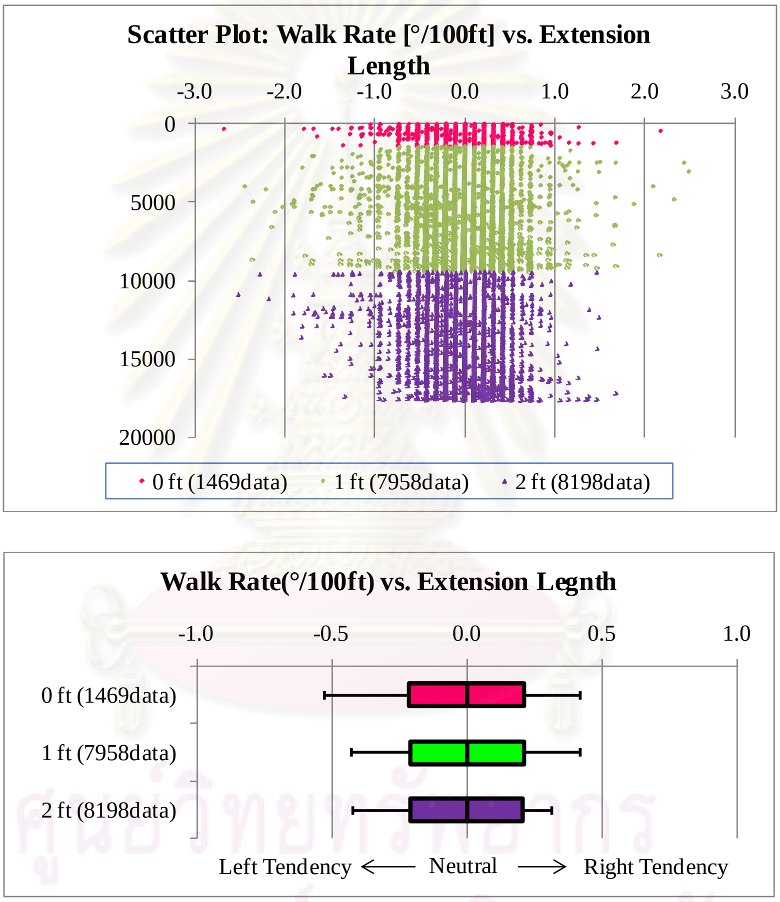


Figure 4-12: Relationship of extension length vs. walk rate in scatter plot and percentile

From Figure 4-12, BHA with every extension length had median walk rate equal to 0 deg/100ft, and had P25 and P75 equal to -0.21 and 0.21 deg/100ft. Therefore it could be concluded that the change in walk rate was not affected by the extension length because BHA with 0ft, 1ft and 2ft had the same walk rate value.

4.3.3 Hole angle vs. walk rate

Walk rate and inclination data point was plotted on scatter plot as shown in Figure 4-13(Top). The walk rate in deg/100ft was plotted on horizontal axis and inclination was plotted on vertical axis. Each dot color represented each hole angle's group. Walk rate data also presented with median and P10, P25, P75 and P90 as shown in Figure 4-13 (Bottom).

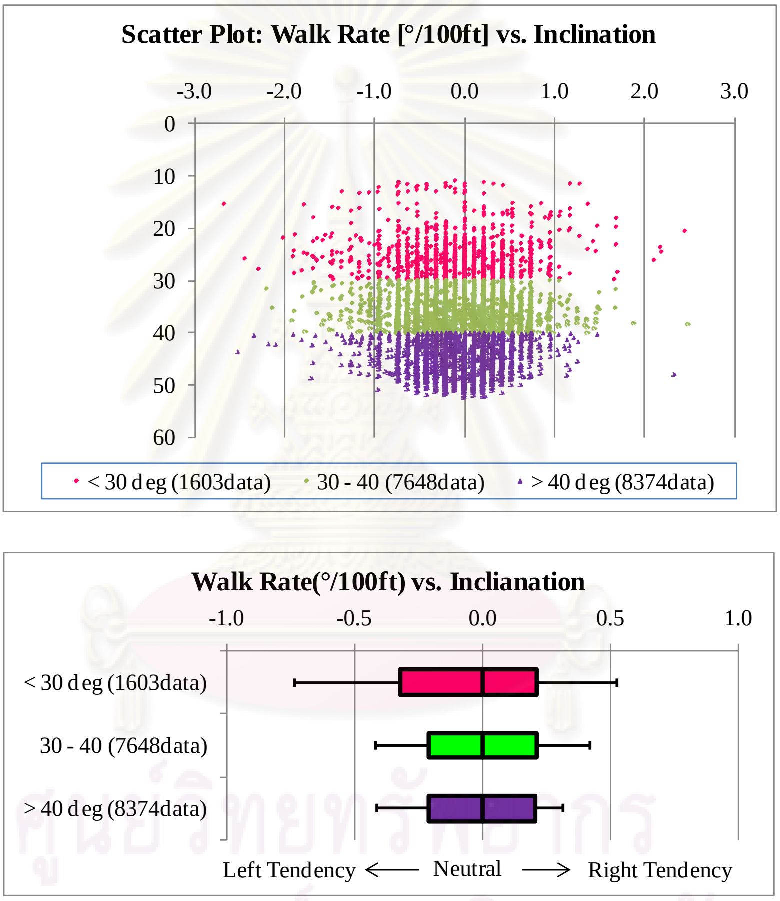


Figure 4-13: Relationship of hole angle vs. walk rate in scatter plot and percentile

From the scatter plot in Figure 4-13, higher hole angle appeared to be less disperse and to walk toward neutral tendency. Every hole angle's group had median walk rate of 0 deg/100ft. However the hole angle < 30 deg had high dispersion, the P10 and P90 was equal -0.8 and 0.5 deg/100ft or 1.3 deg/100ft dispersion.

It could be concluded from Figure 4-13 that the walk rate was affected by hole angle, BHA had more neutral walk tendency and more predictability with higher hole angle.

4.3.4 TVD vs. walk rate

Walk rate and TVD data point was plotted on scatter plot as shown in Figure 4-14(Top). The walk rate in deg/100ft was plotted on horizontal axis and the TVD depth in feet was plotted on vertical axis. Each dot color represented each TVD's group. Walk rate data also presented with median and P10, P25, P75 and P90 as shown in Figure 4-14 (Bottom).

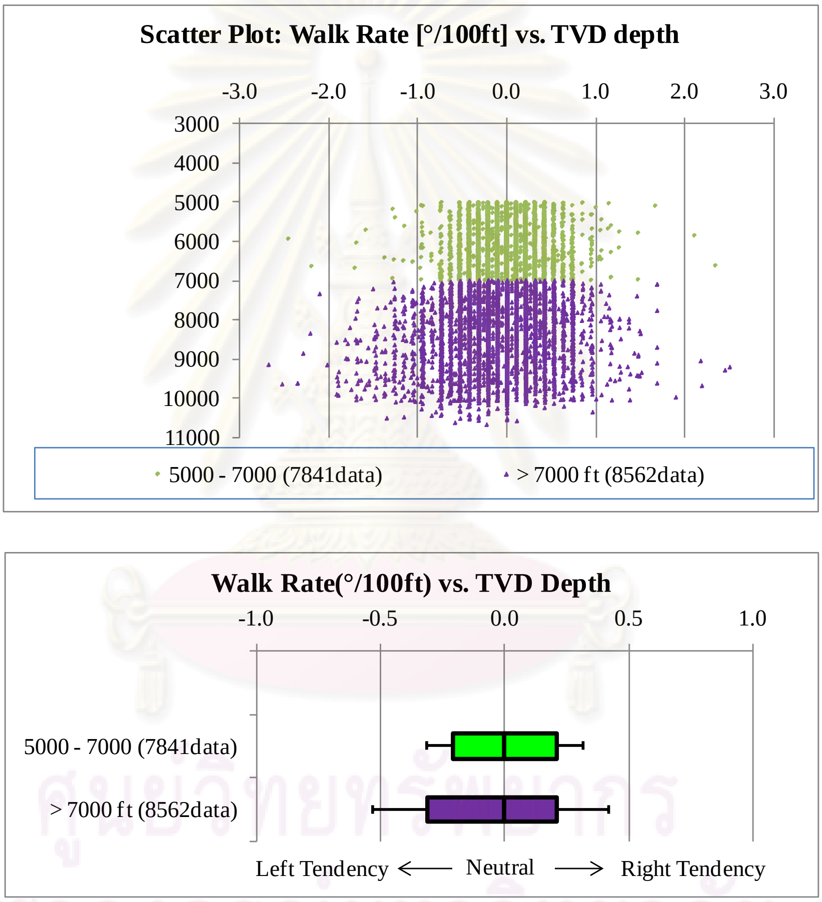
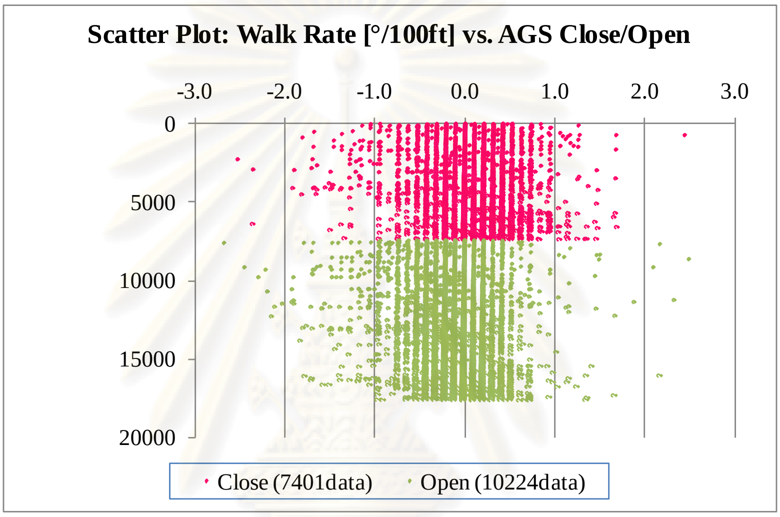


Figure 4-14: Relationship of TVD vs. walk rate in scatter plot and percentile

From Figure 4-14, each TVD group had median walk rate of 0 deg/100ft however from the scatter plot, deeper in TVD appeared to be more dispersed and walk more to the left. It could be concluded that the walk rate was affected by TVD, and bit walked more to the left and had higher dispersion at deeper TVD.

4.3.5 AGS setting vs. walk rate

Walk rate and AGS setting data point was plotted on scatter plot as shown in Figure 4-15(Top). Each dot color represented each AGS setting and the amount of data points was shown in the vertical axis and on the label. Walk rate data for each AGS setting also presented with median and P10, P25, P75 and P90 as shown in Figure 4-15 (Bottom).



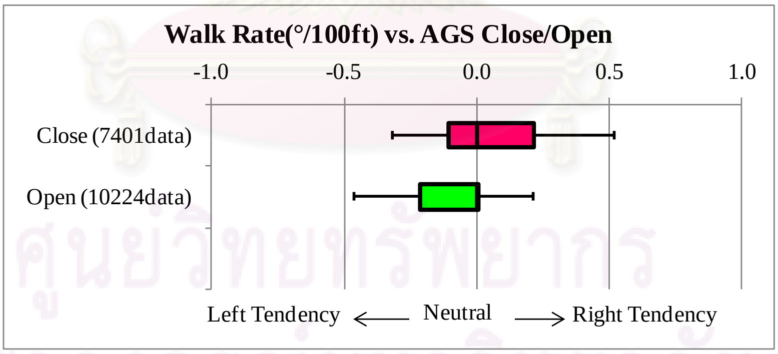
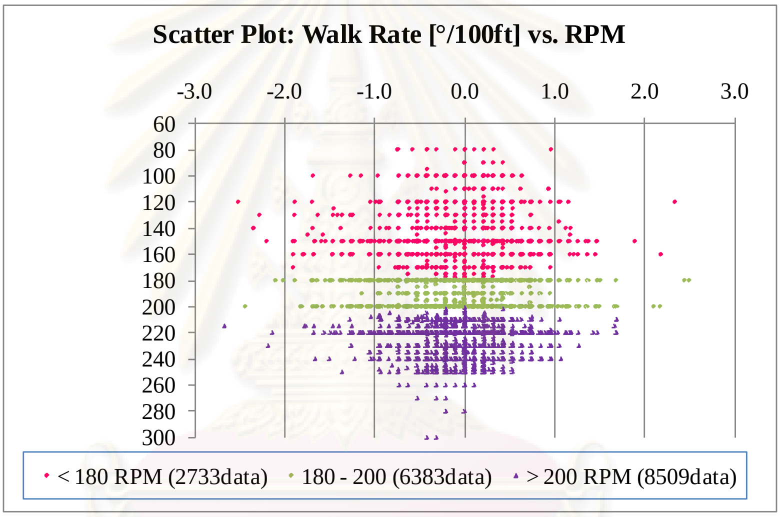


Figure 4-15: Relationship of AGS setting vs. walk rate in scatter plot and percentile

From Figure 4-15, AGS in both setting had median walk rate of 0 deg/100ft, however by comparing the walk rate using P10, P25, P75 and P90, the AGS in close setting had right walk tendency and had higher dispersion while AGS in open setting had left hand walk tendency. Therefore it could be concluded that the walk rate was affected by the AGS setting, bit walked to the right when AGS close and walked to the left when AGS open. Higher walk rate dispersion shown when AGS in close setting.

4.3.6 RPM vs. walk rate

Walk rate and RPM data point was plotted on scatter plot as shown in Figure 4-16(Top). The walk rate in deg/100ft was plotted on horizontal axis and the RPM was plotted on vertical axis. Each dot color represented each RPM's group. Walk rate data also presented with median and P10, P25, P75 and P90 as shown in Figure 4-16 (Bottom).



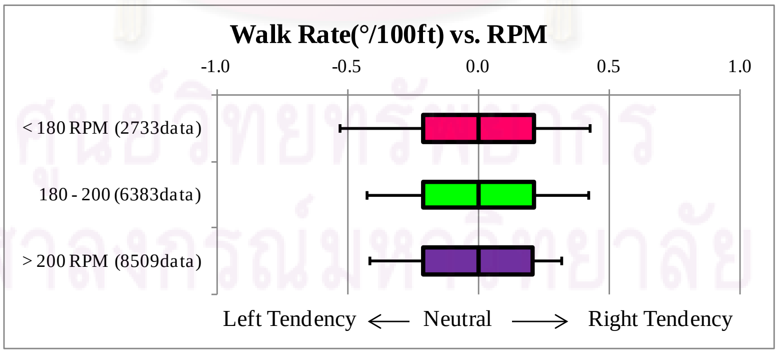
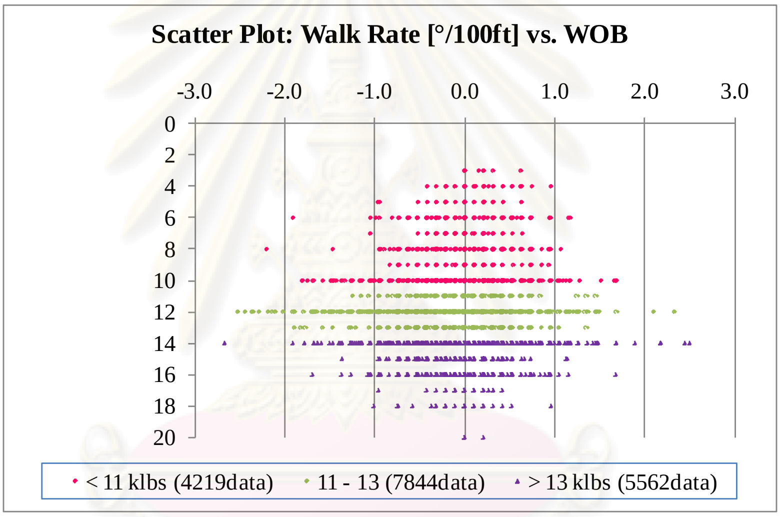


Figure 4-16: Relationship of RPM vs. walk rate in scatter plot and percentile

From Figure 4-16, every RPM had median walk rate of 0 deg/100ft, and had the P25 and P75 equal to -0.21 and 0.21 deg/100ft. Therefore it could be concluded that the change in walk rate was not affected by the change in RPM because every RPM's group had the same walk rate value.

4.3.7 WOB vs. walk rate

Walk rate and WOB data point was plotted on scatter plot as shown in Figure 4-17(Top). The walk rate in deg/100ft was plotted on horizontal axis and the WOB was plotted on vertical axis. Each dot color represented each WOB's group. Walk rate data also presented with median and P10, P25, P75 and P90 as shown in Figure 4-17 (Bottom).



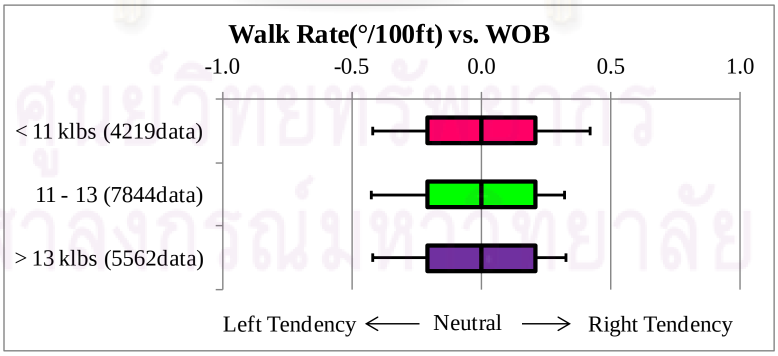


Figure 4-17: Relationship of WOB vs. walk rate in scatter plot and percentile

From Figure 4-17, every WOB had median walk rate of 0 deg/100ft, and had the P25 and P75 equal to -0.21 and 0.21 deg/100ft. Therefore it could be concluded that the change in walk rate was not affected by the change in WOB because every WOB's group had the same walk rate value.

4.3.8 Result summary and discussion

Results of the relationship of seven parameters to the walk rate (Section 4.3.1 to 4.3.7) have been summarized in Figure 4-18.

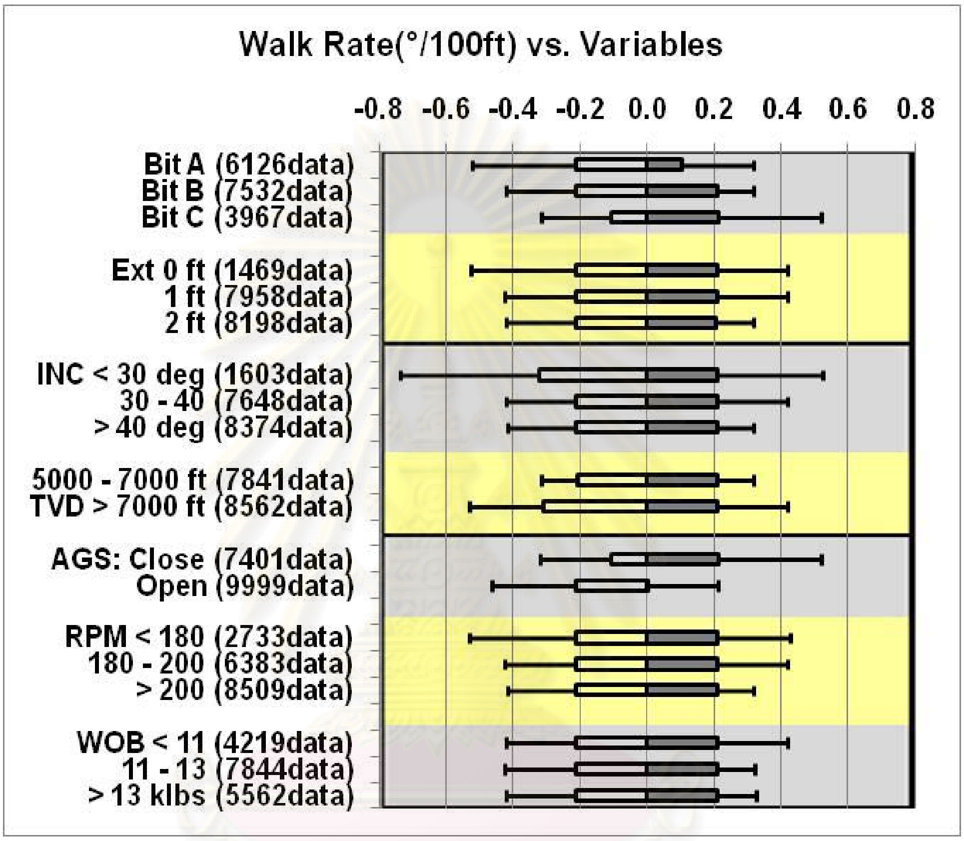


Figure 4-18: Relationship between walk rate and parameters

Walk rate data of each parameter was summarized using the median and P10, P25, P75 and P90 to represent its tendency and its dispersion. From this summary chart it could be concluded that:

1) Every group of parameters had median walk rate equal to 0 deg/100ft.

2) By comparing the walk rate using the P25 and P75, factors that affect walk rate could be ranked as following; AGS setting, bit model, hole angle and TVD equal to 0.2, 0.1, 0.06 & 0.05 deg/100ft respectively. And the changes in extension length, WOB & RPM did not show an effect to the change in walk rate.

3) By comparing the walk rate using the P25 and P75, Bit-A, Bit-B and Bit-C had tendency to walk left, neutral and right respectively. And when AGS close, the bit had tendency to walk more to right compared to when AGS open.

4) By comparing the walk rate dispersion using P25 and P75, deeper in TVD depth, low hole angle < 30deg and AGS in close setting appeared to have higher dispersion compared with other groups.

5) By using P10 and P90, when hole angle < 30deg, the walk rate had the largest dispersion from -0.8 to 0.5 deg/100ft or 1.3 deg/100ft dispersion.

4.4 Established relationship of each parameter to the walk rate with constraints

The average walk rate that we measured from every survey station is the summation of the walk induced by several factors. At this stage, we will find the relationship between each parameter and the walk rate with other parameters constrained in order that the walk rate induced by other parameters can be minimized. Walk rate value was presented using the median and 10th, 25th, 75th, 90th percentile (P10, P25, P75 and P90) to define its tendency and its dispersion. Median was selected to represent the walk rate tendency because we are coping with a large amount of repeated values and our objective was to predict the walk rate, therefore the median was more suitable to use.

There were total 7 parameters included in this study. When performed the study of the relationship between one parameter and the walk rate, the other 6 parameters were fixed. There were total of 108 scenarios as shown in Table 4-14. For RPM and WOB, only middle range of RPM and WOB (180-200 RPM and 11-13 klbs) was used. Scenarios in Table 4-14 could be presented differently as shown in Figure 4-19. From Figure 4-19, there were nine BHA configurations, six cases of hole angle and TVD with constrained RPM & WOB and two setting of AGS giving total of 108 scenarios.

Table 4-14: Total scenarios for studying the walk rate of each parameter

no.	Parameters	Group1	Group2	Group3	Scenarios
1	Bit Model	Bit-A	Bit-B	Bit-C	3
2	Extension (ft)	0ft	1ft	2ft	3
3	Hole Angle (deg)	< 30	30-40	>40	3
4	TVD depth (ft)	5000 - 7000	> 7000		2
5	AGS setting	close	open		2
7	RPM	< 180	180 - 200	> 200	1
6	WOB (klbs)	< 11 klbs	11-13 klbs	> 13 klbs	1
Total Scenarios = 3 x 3 x 3 x 2 x 2 x 1 x 1					108

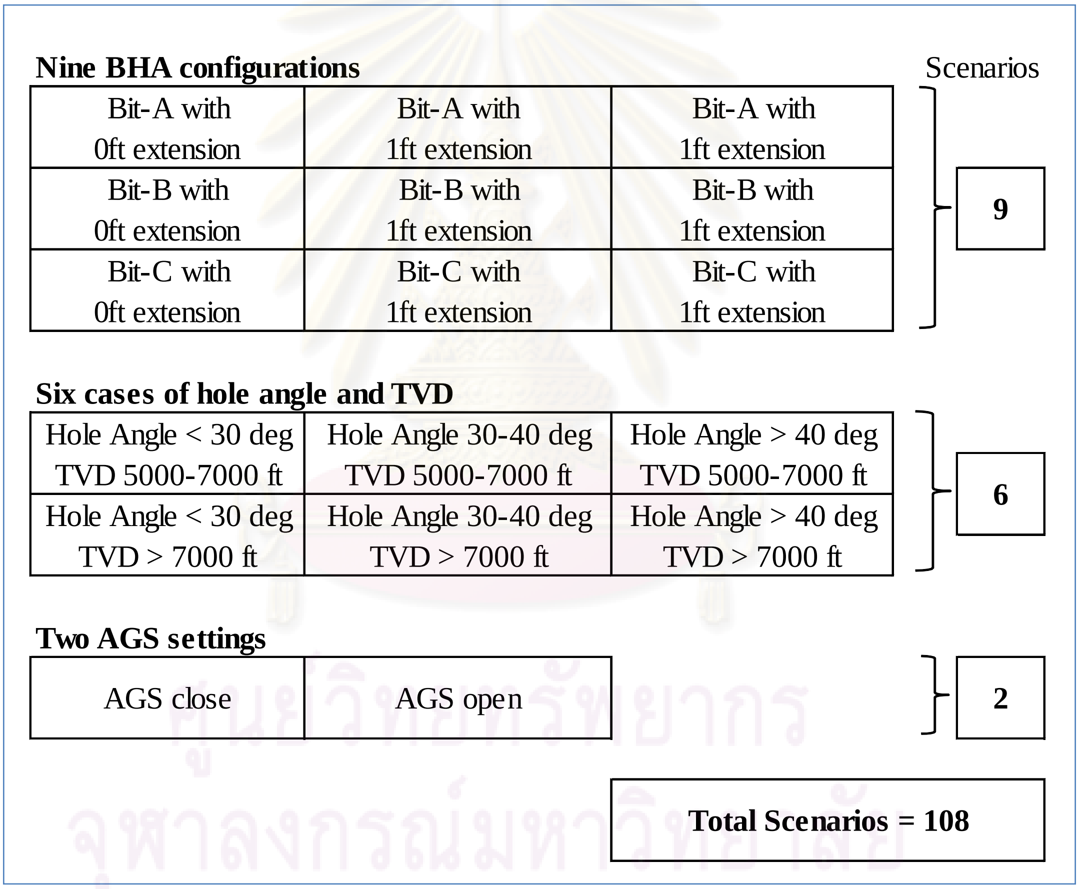


Figure 4-19: Total scenarios for studying the walk rate of each parameter

4.4.1 Bit model vs. walk rate

The walk rate of nine BHA configurations in six cases of hole angle and TVD with constrained RPM & WOB, and two setting of AGS was presented. The constraints for studying the effect of bit model to walk rate were shown in Table 4-15 and the results from every scenario were presented in Figure 4-20 to Figure 4-22.

Table 4-15: Constraints for studying the effect of bit model to walk rate

	RPM	WOB	Inc	TVD	AGS
Case1-1	180-200	11-13 klbs	< 30 deg	5000-7000ft	Close
Case1-2	180-200	11-13 klbs	< 30 deg	5000-7000ft	Open
Case2-1	180-200	11-13 klbs	30-40 deg	5000-7000ft	Close
Case2-2	180-200	11-13 klbs	30-40 deg	5000-7000ft	Open
Case3-1	180-200	11-13 klbs	> 40 deg	5000-7000ft	Close
Case3-2	180-200	11-13 klbs	> 40 deg	5000-7000ft	Open
Case4-1	180-200	11-13 klbs	< 30 deg	> 7000ft	Close
Case4-2	180-200	11-13 klbs	< 30 deg	> 7000ft	Open
Case5-1	180-200	11-13 klbs	30-40 deg	> 7000ft	Close
Case5-2	180-200	11-13 klbs	30-40 deg	> 7000ft	Open
Case6-1	180-200	11-13 klbs	> 40 deg	> 7000ft	Close
Case6-2	180-200	11-13 klbs	> 40 deg	> 7000ft	Open

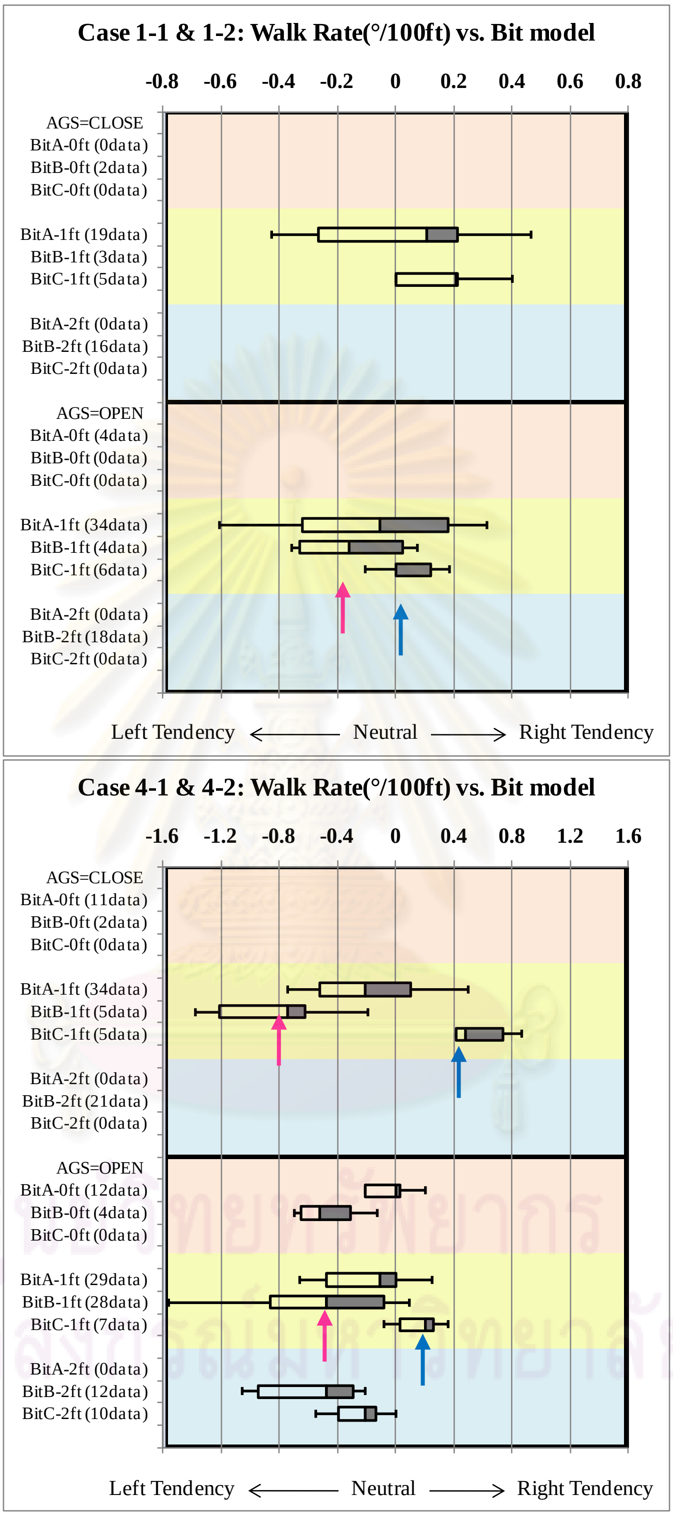
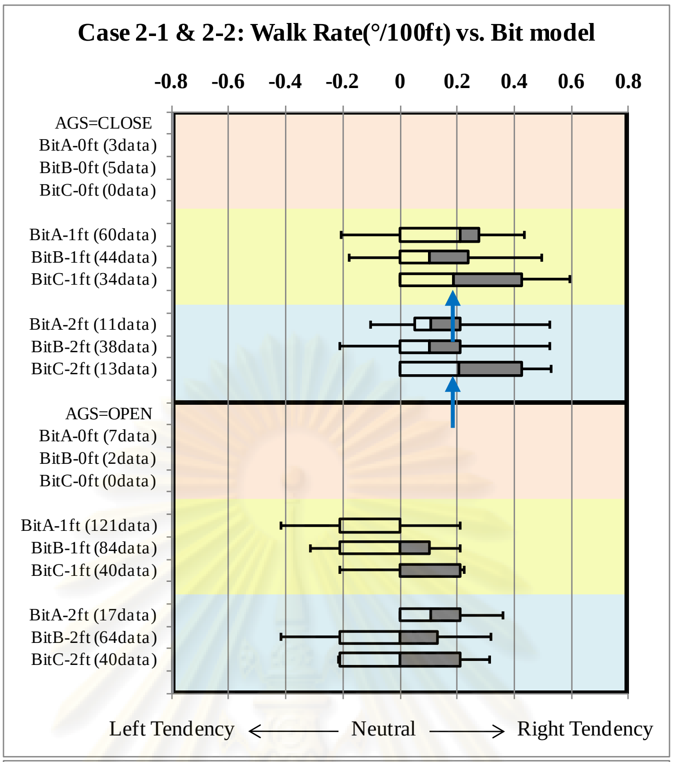


Figure 4-20: Relationship of bit model vs. walk rate. Hole angle < 30 deg. Case1 (TVD 5000-7000ft) and Case4 (TVD > 7000ft)

From Figure 4-20 Case1 and 4, Bit-C had the most right hand walk tendency (blue arrow) and Bit-B had the most left hand walk tendency (pink arrow).



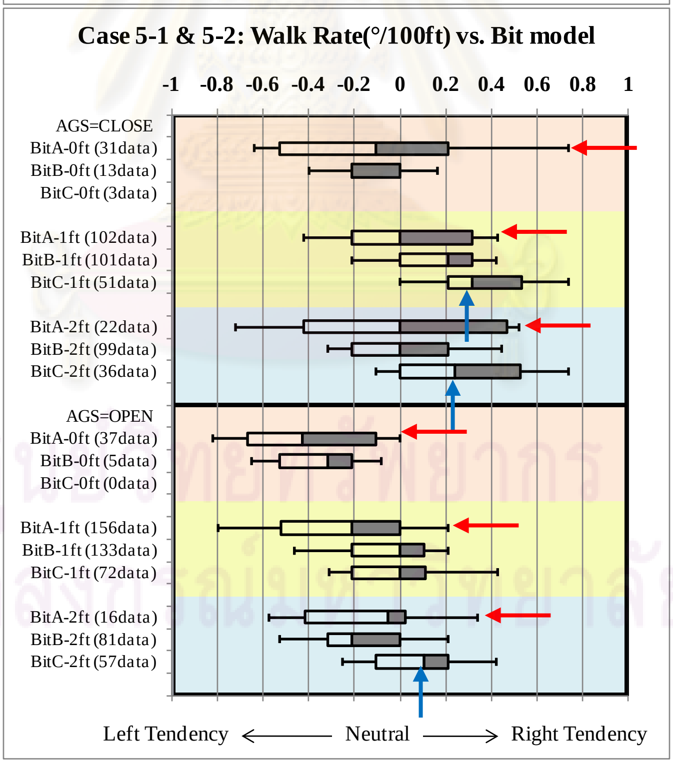


Figure 4-21: Relationship of bit model vs. walk rate. Hole angle 30-40 deg. Case2 (TVD 5000-7000ft) and Case5 (TVD > 7000ft)

From Figure 4-21 Case2 and 5, Bit-C had the most right hand walk tendency (blue arrow) and Bit-A showed higher dispersion in walk rate than other bit models when TVD > 7000 ft (red arrow).

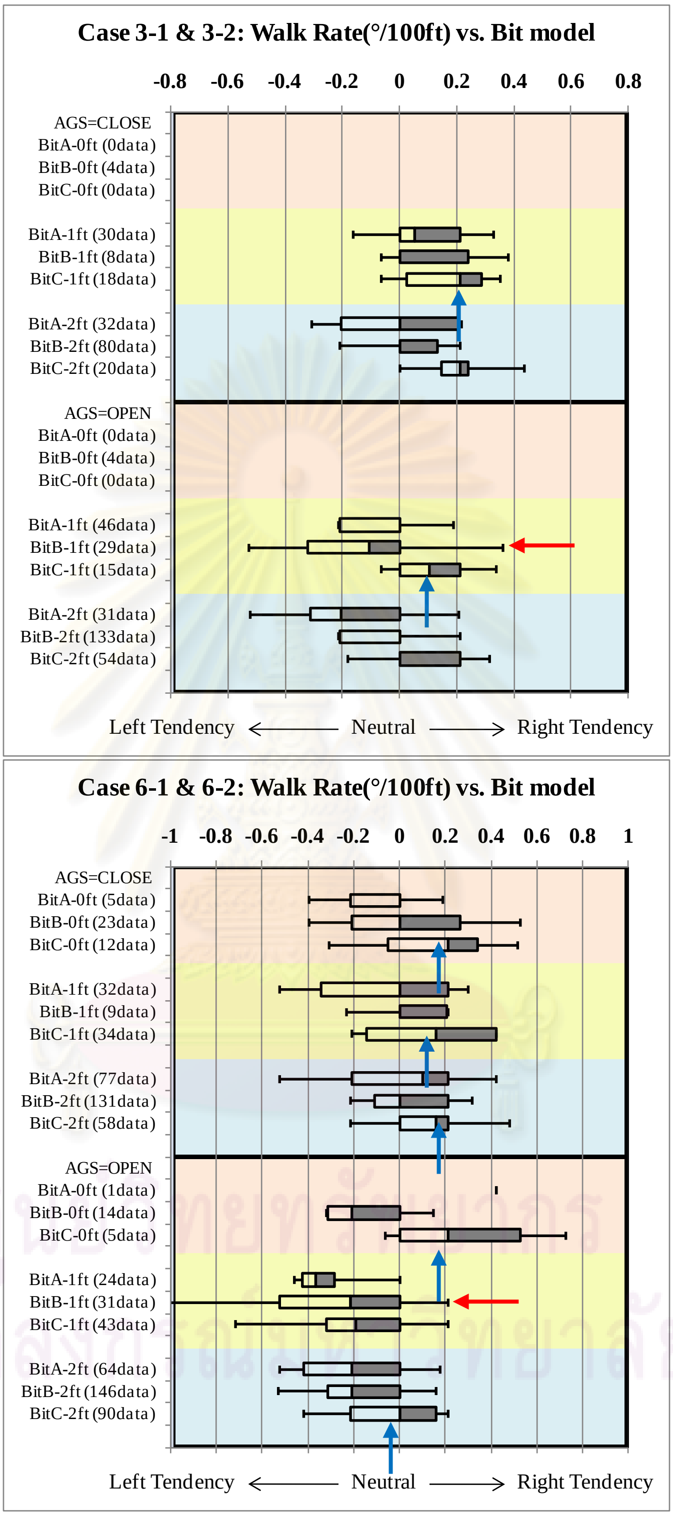


Figure 4-22: Relationship of bit model vs. walk rate. Hole angle > 40 deg. Case3 (TVD 5000-7000ft) and Case6 (TVD > 7000ft)

From Figure 4-22 Case3 and 6, Bit-C had the most right hand walk tendency (blue arrow) and Bit-B with 1ft extension showed higher dispersion in walk rate compared to other bit models when AGS open (red arrow).

From results of every scenario, it could be concluded that the bit model had effect on the walk rate, and these three different bit models gave different average walk rates ranging from 0 to 1.2 deg/100ft or an average of 0.26 deg/100ft from every scenario. There were observations from their relationships as following:

1) Bit-C had the most right hand walk tendency compared to Bit-A and Bit-B.
2) Bit-B showed the most left hand walk tendency at hole angle < 30 deg.
3) Bit-A showed high dispersion in walk rate at hole angle 30-40 deg and TVD > 7000 ft.
4) Bit-B with 1ft extension showed high dispersion in walk rate at hole angle > 40 deg and AGS in open setting.

4.4.2 Extension length vs. walk rate

The walk rate of nine BHA configurations in six cases of hole angle and TVD with constrained RPM & WOB and two setting of AGS was presented. The constraints for studying the effect of extension length to walk rate was shown in Table 4-16 and the results from every scenario were presented in Figure 4-23 to Figure 4-25.

Table 4-16: Constraints for studying the effect of extension length to walk rate

	RPM	WOB	Inc	TVD	AGS
Case1-1	180-200	11-13 klbs	< 30 deg	5000-7000ft	Close
Case1-2	180-200	11-13 klbs	< 30 deg	5000-7000ft	Open
Case2-1	180-200	11-13 klbs	30-40 deg	5000-7000ft	Close
Case2-2	180-200	11-13 klbs	30-40 deg	5000-7000ft	Open
Case3-1	180-200	11-13 klbs	> 40 deg	5000-7000ft	Close
Case3-2	180-200	11-13 klbs	> 40 deg	5000-7000ft	Open
Case4-1	180-200	11-13 klbs	< 30 deg	> 7000ft	Close
Case4-2	180-200	11-13 klbs	< 30 deg	> 7000ft	Open
Case5-1	180-200	11-13 klbs	30-40 deg	> 7000ft	Close
Case5-2	180-200	11-13 klbs	30-40 deg	> 7000ft	Open
Case6-1	180-200	11-13 klbs	> 40 deg	> 7000ft	Close
Case6-2	180-200	11-13 klbs	> 40 deg	> 7000ft	Open

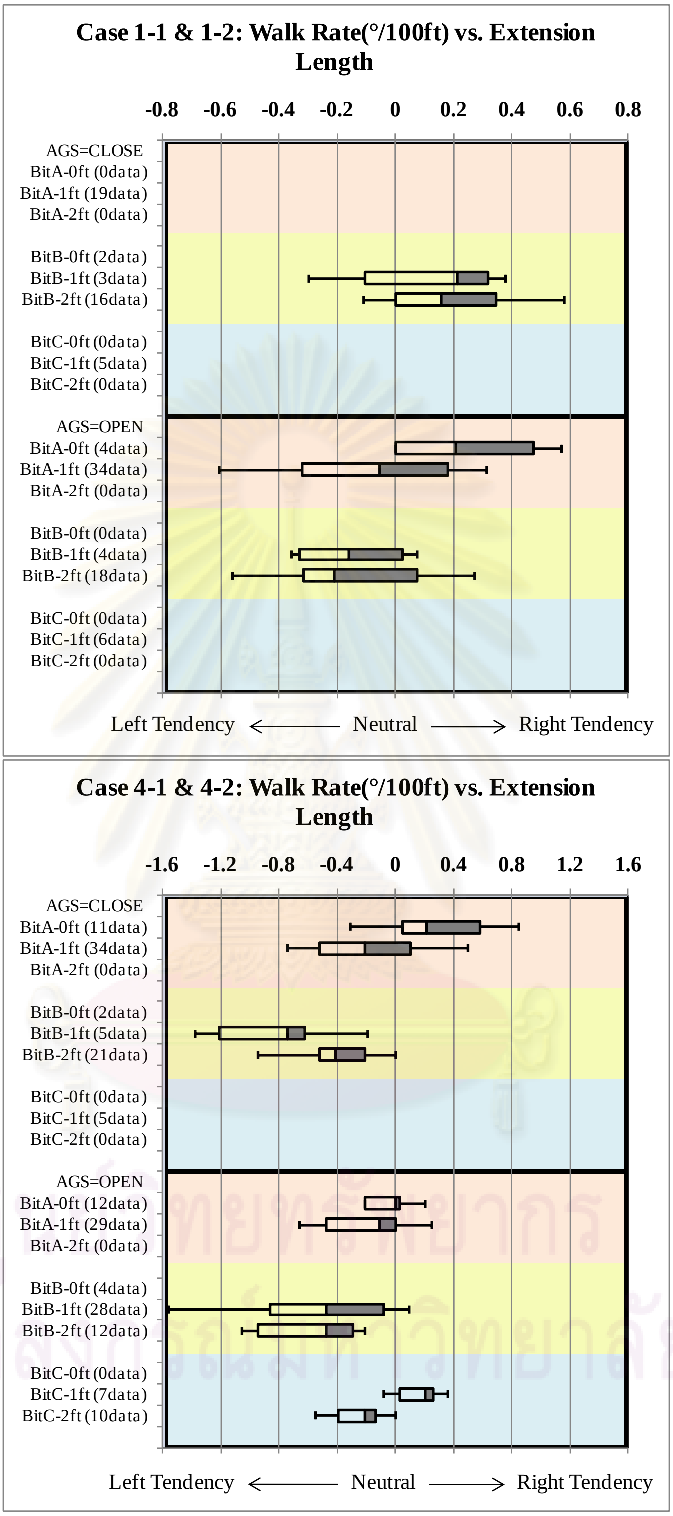


Figure 4-23: Relationship of extension length vs. walk rate. Hole angle < 30 deg. Case1 (TVD 5,000 – 7,000 ft) and Case4 (TVD > 7,000 ft)

There was no discussion of Case1 and 4 in Figure 4-23 because the data points were limited.

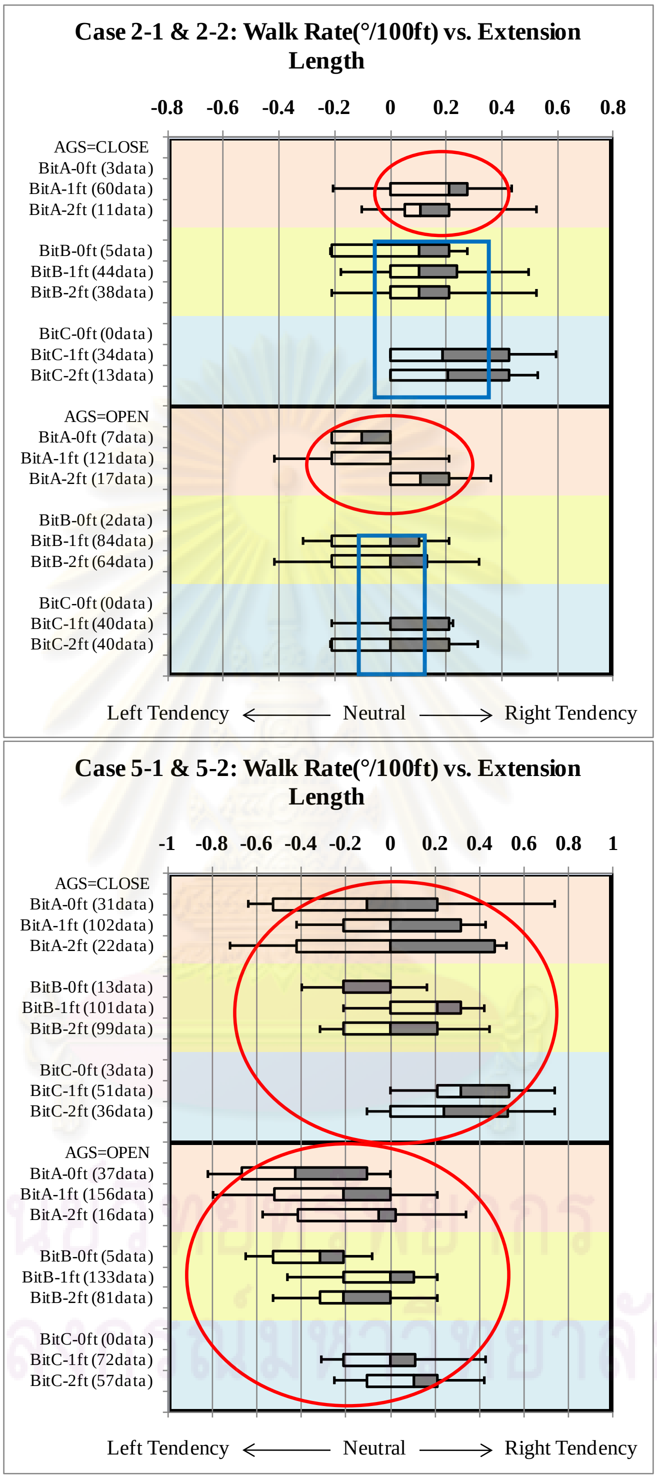


Figure 4-24: Relationship of extension length vs. walk rate. Hole angle 30-40 deg. Case2 (TVD 5,000 – 7,000 ft) and Case5 (TVD > 7,000 ft)

From Figure 4-24 Case 2 and 5, different in extension length had minimum effect on walk rate of Bit-B and Bit-C when TVD 5,000-7,000 ft (blue rectangular) evidenced by having similar median walk rate, but it showed an effect on walk rate of Bit-A,TVD 5,000-7,000 ft and every bit when TVD > 7,000 ft (red rectangular).

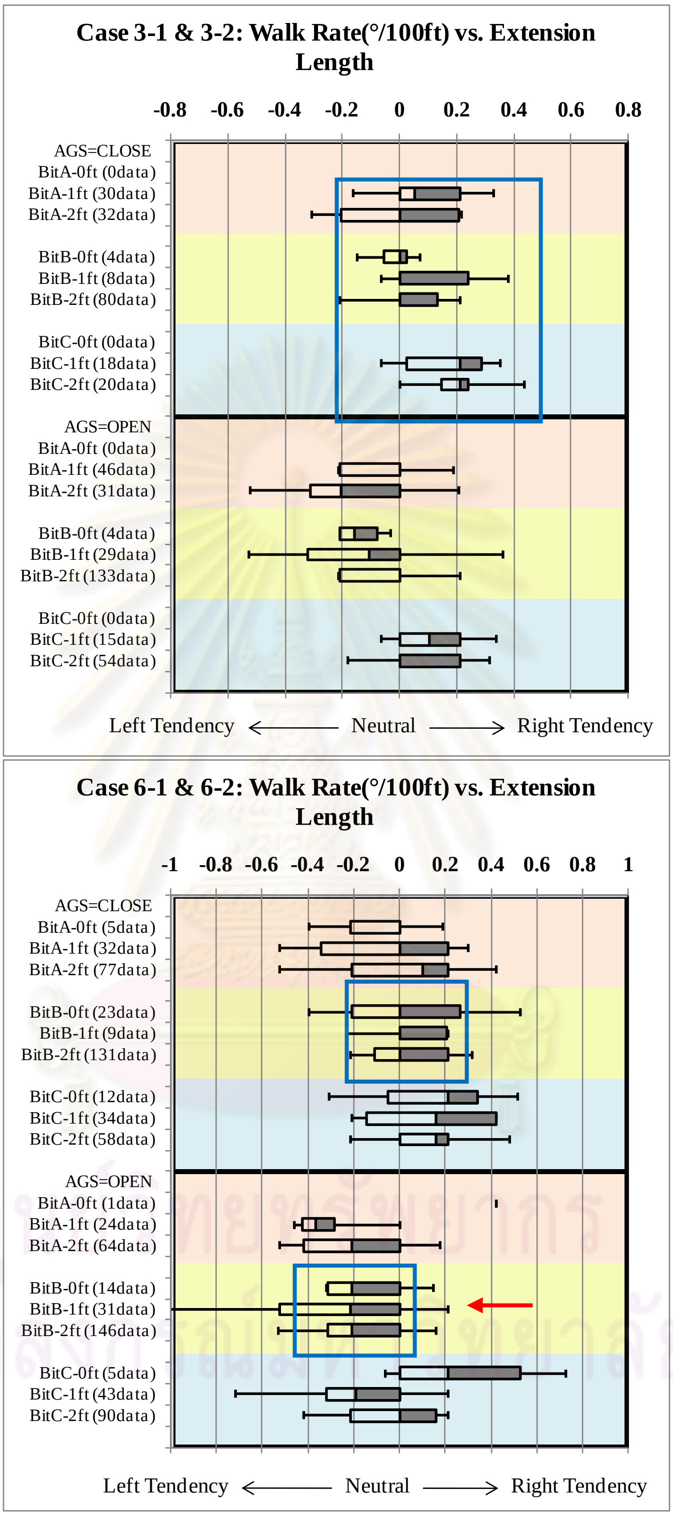


Figure 4-25: Relationship of extension length vs. walk rate. Hole angle > 40 deg. Case3 (TVD 5,000 – 7,000ft) and Case6 (TVD > 7,000ft)

From Figure 4-25 Case3, different in extension length had minimum effect on walk rate when close AGS (blue rectangular) evidenced by having the similar median walk rate. From Figure 4-25 Case6, different in extension did not have effect on walk rate for Bit-B with 1ft extension (blue rectangular) evidenced by having the similar median walk rate. And Bit-B with 1ft extension had larger walk rate dispersion compared to other configurations (red arrow).

From results of every scenario, it could be concluded that the extension length had effect on the walk rate. Changing the extension length caused the change in average walk rate ranging from 0 to 0.4 deg/100ft. However the relationships between extension length and walk rate were not linear. There are observations of their relationships as following:

1) At hole angle 30-40 deg, TVD 5000-7000 ft, different in extension length did not have effect on walk rate of Bit-B and Bit-C, but showed an effect on walk rate of Bit-A.

2) At hole angle >40 deg, TVD 5000-7000 ft, different in extension length had minimum effect on walk rate of Bit-A, Bit-B and Bit-C when close AGS.

3) At hole Angle > 40 deg, TVD > 7000 ft, different in extension length had minimum effect on walk rate of Bit-B. And Bit-B, 1ft extension, AGS open had larger walk rate dispersion compared to other configurations.

4.4.3 Hole angle vs. walk rate

The walk rate of nine BHA configurations in two TVD cases with constrained RPM & WOB and two setting of AGS were presented. The constraints for studying the effect of hole angle to walk rate was shown in Table 4-17 and the results from every scenario were presented in Figure 4-26 to Figure 4-27.

Table 4-17: Constraints for studying the effect of hole angle to walk rate

	RPM	WOB	TVD	AGS
Case1-1	180-200	11-13 klbs	5000-7000ft	Close
Case1-2	180-200	11-13 klbs	5000-7000ft	Open
Case2-1	180-200	11-13 klbs	> 7000ft	Close
Case2-2	180-200	11-13 klbs	> 7000ft	Open

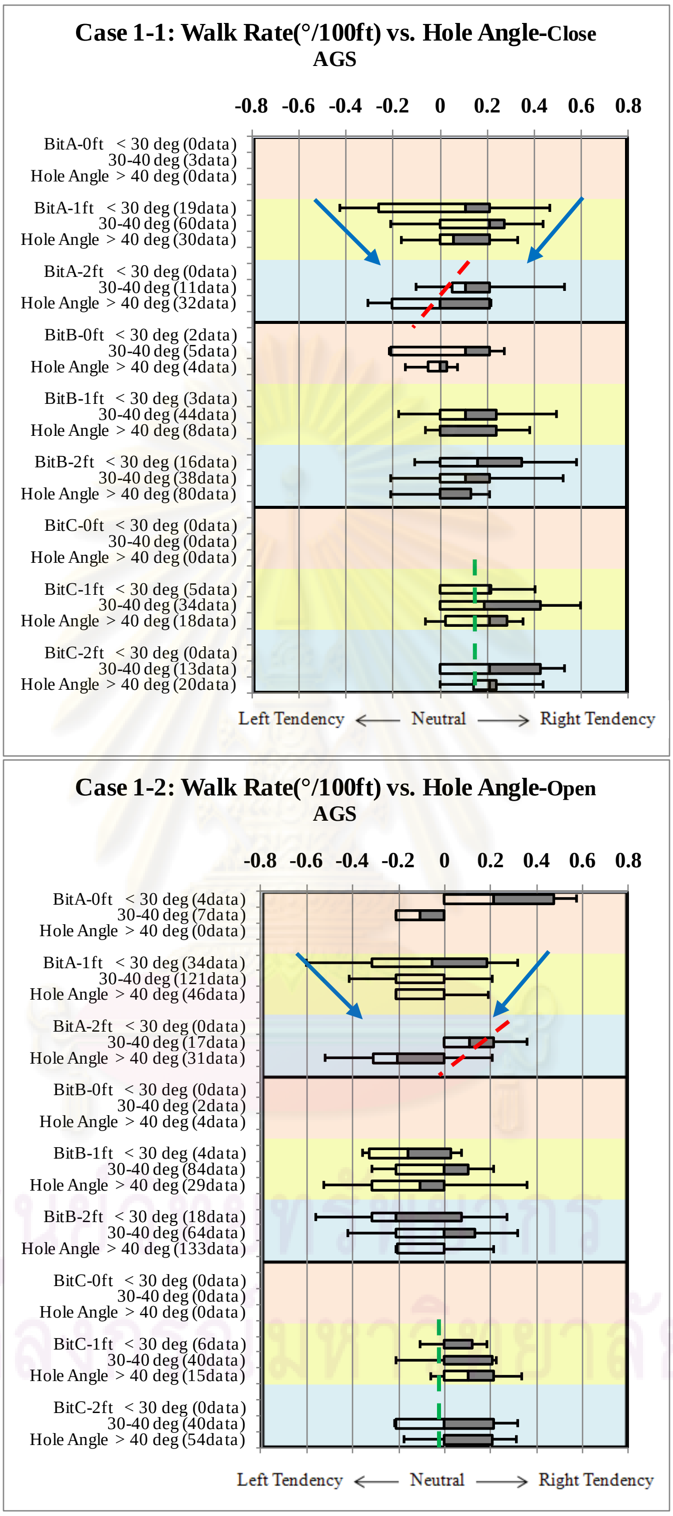


Figure 4-26: Relationship of hole angle vs. walk rate. Case1 (TVD 5000 - 7000 ft).

From Figure 4-26 Case1, Bit-A with 1ft extension had more disperse in walk rate with lower hole angle (blue arrow). Bit-A with 2ft extension had more left hand walk with higher hole angle (red dash line) and Bit-C with 1ft and 2ft extension had minimal effect from hole angle to the walk rate (green dash line), evidenced by having similar median walk rate.

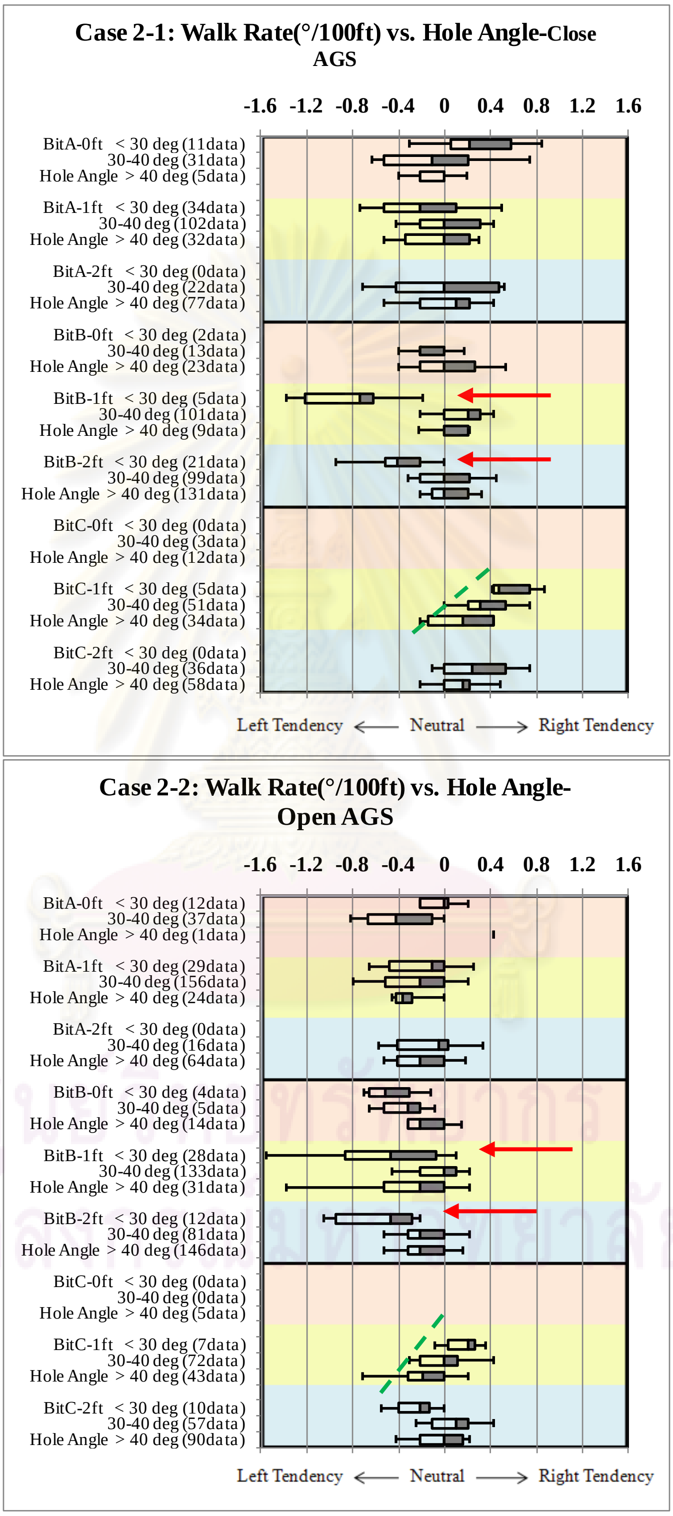


Figure 4-27: Relationship of hole angle vs. walk rate. Case2 (TVD > 7000 ft)

From Figure 4-27 Case2, Bit-B, 1ft and 2ft extension had large dispersion in walk rate with hole angle < 30deg (red arrow). And Bit C with 1ft extension walked more to the left with higher hole angle (green dash line).

From results of every scenario, it could be concluded that the hole angle had effect on the walk rate. Increasing hole angle caused the change in average walk rate ranging from 0 to 1 deg/100ft or an average of 0.24 deg/100ft. However the relationship between hole angle and walk rate were not linear. There are observations of their relationships as following:

1) At TVD 5000-7000ft, Bit-A, 1 ft extension had larger dispersion in walk rate with lower hole angle. Bit-A, 2ft extension walked more to the left with higher hole angle and Bit-C, 1ft and 2ft extension had minimal effect from hole angle to the walk rate.
2) At TVD > 7000ft, Bit-B, 1ft and 2ft extension had high disperse in walk rate with hole angle < 30deg and Bit C, 1ft extension walked more to the left with higher hole angle.

4.4.4 TVD vs. walk rate

The walk rate of nine BHA configurations in three hole angle cases and two setting of AGS were presented. The constraints for study the effect of TVD to walk rate was shown in Table 4-18 and the results from every scenario were present in Figure 4-28 to Figure 4-30.

Table 4-18: Constraints for study the effect of TVD to walk rate

	RPM	WOB	Inc	AGS
Case1-1	180-200	11-13 klbs	< 30 deg	Close
Case1-2	180-200	11-13 klbs	< 30 deg	Open
Case2-1	180-200	11-13 klbs	30-40 deg	Close
Case2-2	180-200	11-13 klbs	30-40 deg	Open
Case3-1	180-200	11-13 klbs	> 40 deg	Close
Case3-2	180-200	11-13 klbs	> 40 deg	Open

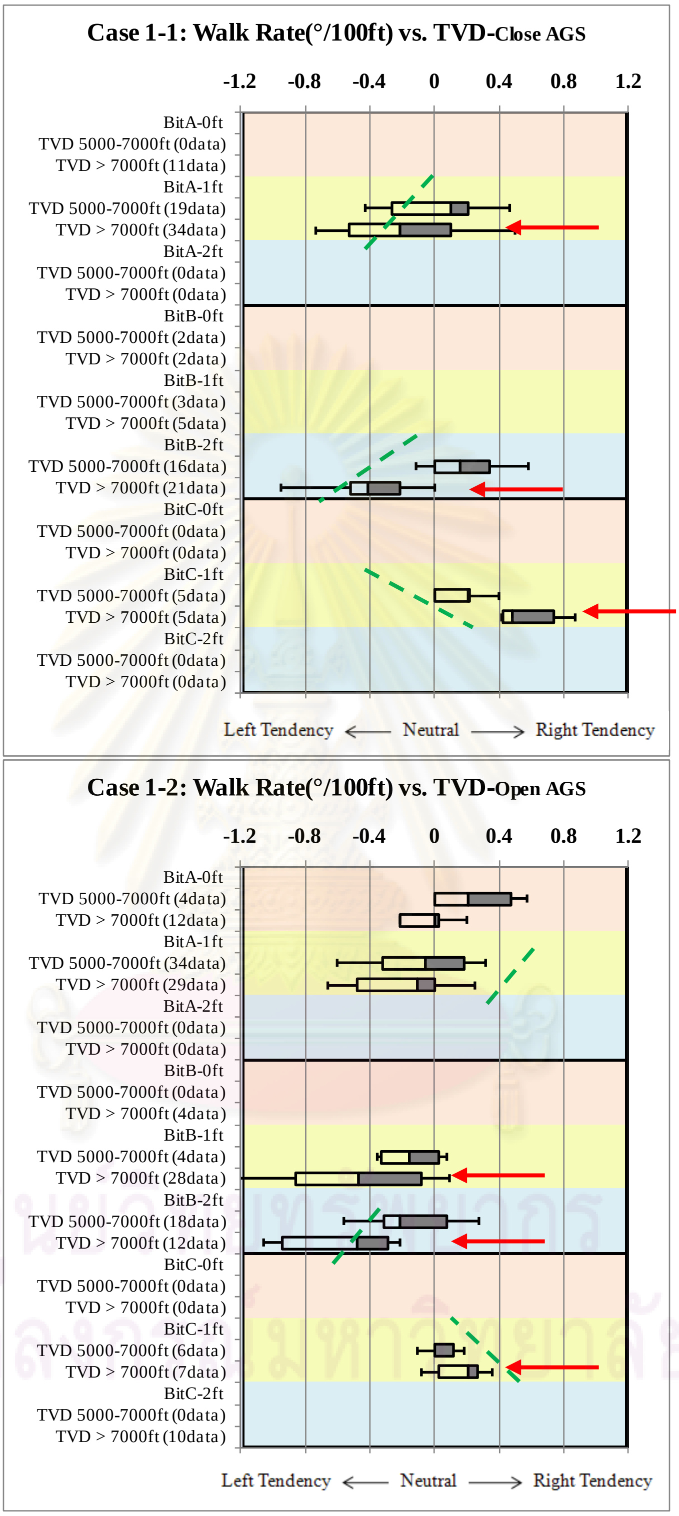


Figure 4-28: Relationship of TVD vs. walk rate. Case1 (hole angle < 30 deg)

From Figure 4-28 Case1, deeper in TVD showed more left hand walk tendency for Bit-A and Bit-B and showed more right hand walk tendency for Bit-C (green dash line). Deeper in TVD showed more dispersion of walk rate for most of BHA configurations (red arrow).

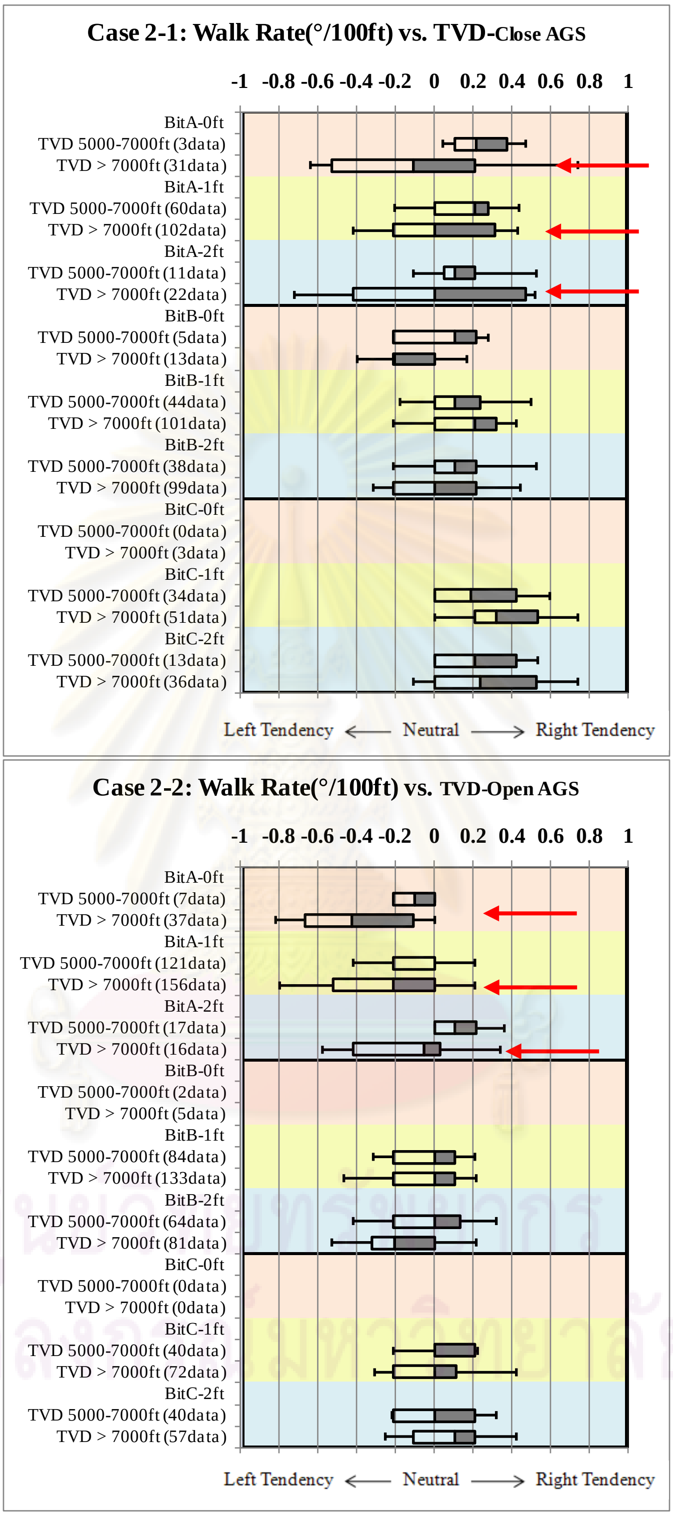


Figure 4-29: Relationship of TVD vs. walk rate. Case2 (hole angle 30-40 deg)

From Figure 4-29 Case 2, deeper in TVD showed more dispersion of walk rate, especially on Bit-A (red arrow).

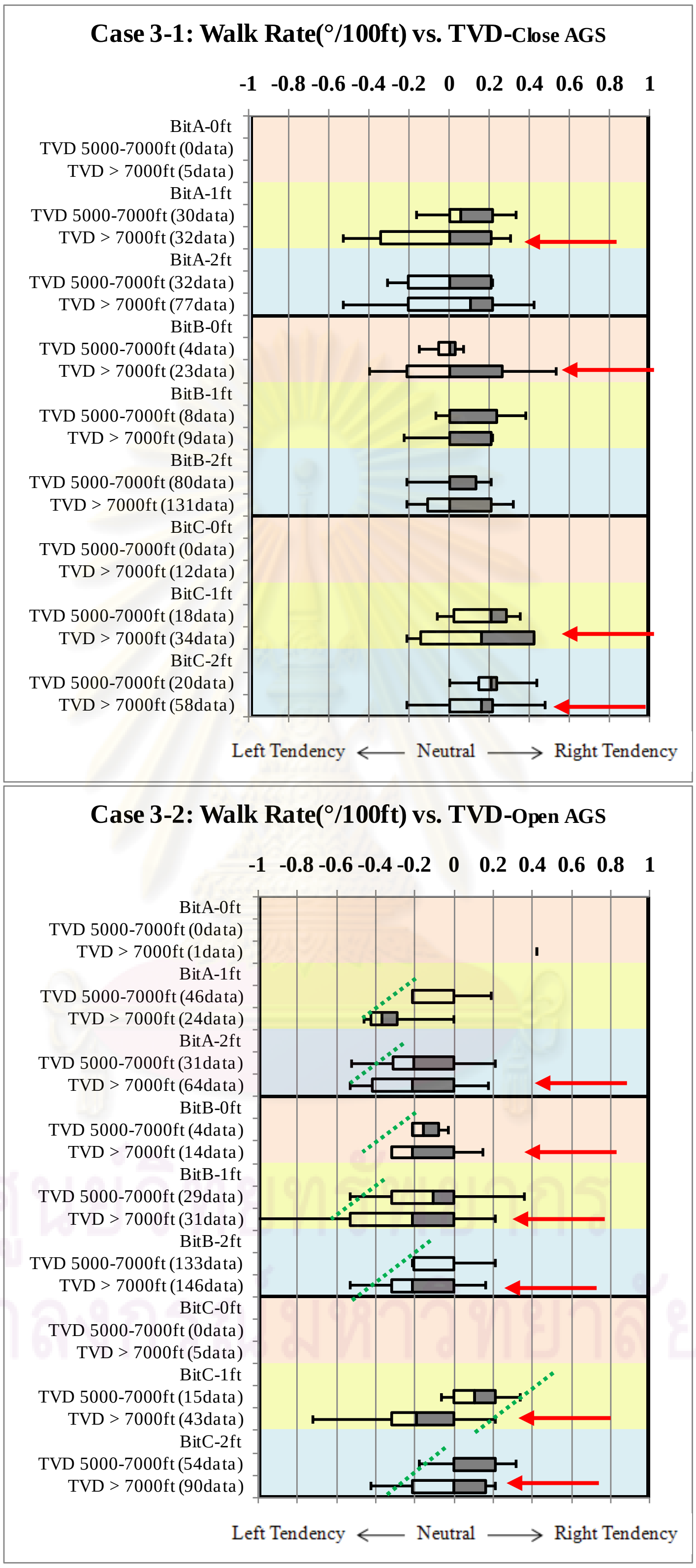


Figure 4-30: Relationship of TVD vs. walk rate. Case3 (hole angle > 40 deg)

From Figure 4-30 Case 3, deeper in TVD showed more dispersion of walk rate for almost every BHA configurations (red arrow). And deeper in TVD showed more left hand walk tendency for all bit models when AGS open (green dash line).

From results of every scenario, it could be concluded that the TVD had effect on the walk rate. Increase TVD depth caused the change in average walk rate ranging from 0 to 0.6 deg/100ft or an average of 0.16deg/100ft. There are observations of their relationships as following:

1) At hole angle < 30, deeper in TVD showed more left hand walk tendency for Bit-A and Bit-B and showed more right hand walk tendency for Bit-C. Deeper in TVD showed more dispersion of walk rate for most BHA configurations.
2) At hole angle 30-40 deg, deeper in TVD showed more dispersion of walk rate especially on Bit-A.
3) At hole angle > 40 deg, deeper in TVD showed more dispersion of walk rate for almost every BHA configurations. And deeper in TVD showed more left hand walk tendency for all bit models when AGS open.

4.4.5 AGS setting vs. walk rate

The walk rate of nine BHA configurations in six case of hole angle and TVD with constrained RPM & WOB and two setting of AGS were presented. The constraints for studying the effect of AGS setting to walk rate was shown in Table 4-19 and the results from every scenario were presented in Figure 4-31 to Figure 4-33.

Table 4-19: Constraints for studying the effect of AGS setting to walk rate

	RPM	WOB	Inc	TVD
Case1	180-200	11-13 klbs	< 30 deg	5000-7000ft
Case2	180-200	11-13 klbs	30-40 deg	> 7000ft
Case3	180-200	11-13 klbs	> 40 deg	5000-7000ft
Case4	180-200	11-13 klbs	< 30 deg	> 7000ft
Case5	180-200	11-13 klbs	30-40 deg	> 7000ft
Case6	180-200	11-13 klbs	> 40 deg	> 7000ft

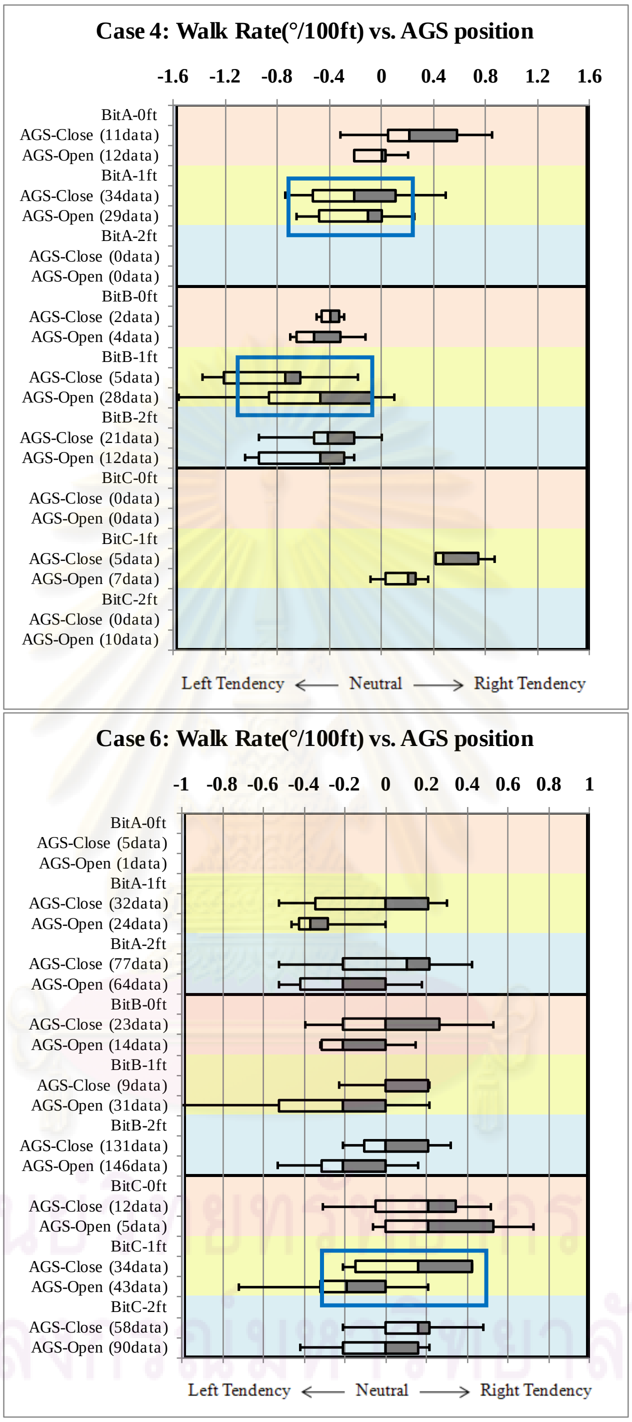


Figure 4-31: Relationship of AGS setting vs. walk rate.TVD>7,000 ft. Case4 (hole angle < 30 deg) and Case6 (hole angle > 40 deg)

From Figure 4-31, the results of every scenario showed that when AGS close, bit walked more to the right compared to AGS open except for 3 scenarios including Bit A & B with 1ft extension, hole angle < 30 deg and TVD >7,000 ft, and Bit-C with 0ft extension, hole angle > 40 deg and TVD >7,000 ft (blue rectangular).

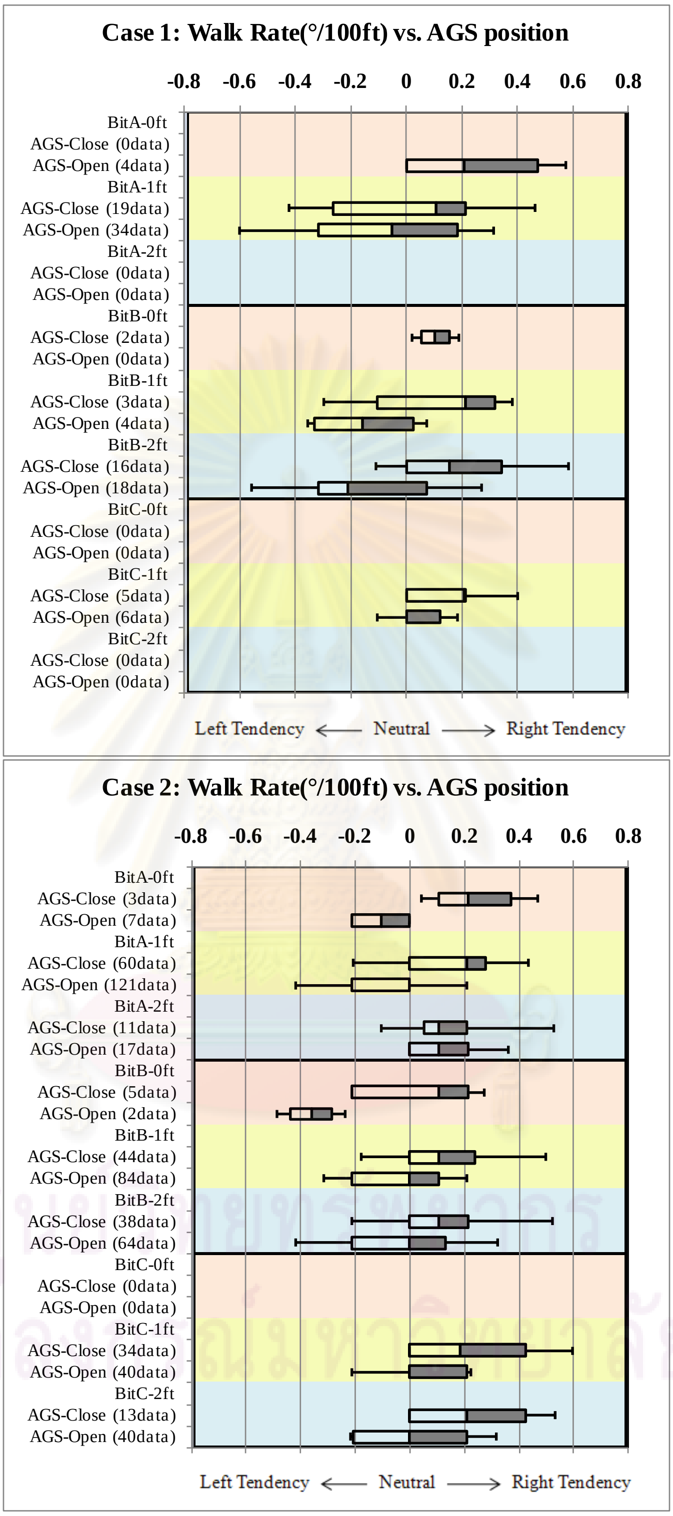


Figure 4-32: Relationship of AGS setting vs. walk rate.TVD 5000-7000ft. Case1 (hole angle < 30deg) and Case2 (hole angle 30-40 deg)

AGS close had more right walk compared to AGS open as shown in Figure 4-32.

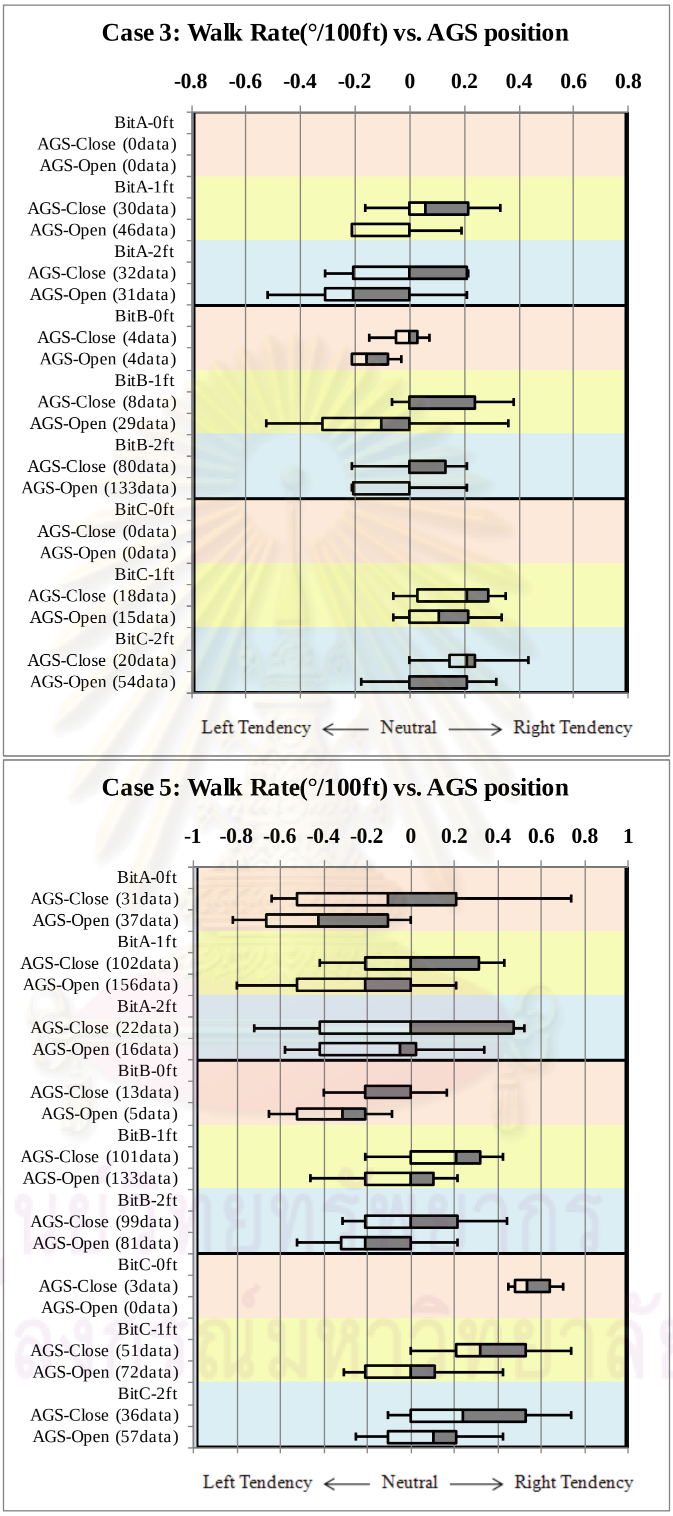


Figure 4-33: Relationship of AGS setting vs. walk rate. Case3(hole angle > 40 deg, TVD 5000-7000ft). Case5 (hole angle 30 - 40deg, TVD > 7000ft)

AGS close had more right walk compared to AGS open as shown in Figure 4-33.

From results of every scenario, it could be concluded that the AGS setting had effect on the walk rate. Changing AGS setting caused change in average walk rate ranging from 0 to 0.5 deg/100ft or an average of 0.20 deg/100ft. AGS in close position walked more to the right compared to AGS in open position.

4.4.6 RPM vs. walk rate

The walk rate of nine BHA configurations in six case of hole angle and TVD with constrained RPM & WOB and two setting of AGS were presented. The constraints for studying the effect of RPM to walk rate was shown in Table 4-20 and the results from every scenario were presented in Figure 4-34 to Figure 4-39.

Table 4-20: Constraints for studying the effect of RPM to walk rate

	WOB	Inc	TVD	AGS
Case1-1	11-13 klbs	< 30 deg	5000-7000ft	Close
Case1-2	11-13 klbs	< 30 deg	5000-7000ft	Open
Case2-1	11-13 klbs	30-40 deg	5000-7000ft	Close
Case2-2	11-13 klbs	30-40 deg	5000-7000ft	Open
Case3-1	11-13 klbs	> 40 deg	5000-7000ft	Close
Case3-2	11-13 klbs	> 40 deg	5000-7000ft	Open
Case4-1	11-13 klbs	< 30 deg	> 7000ft	Close
Case4-2	11-13 klbs	< 30 deg	> 7000ft	Open
Case5-1	11-13 klbs	30-40 deg	> 7000ft	Close
Case5-2	11-13 klbs	30-40 deg	> 7000ft	Open
Case6-1	11-13 klbs	> 40 deg	> 7000ft	Close
Case6-2	11-13 klbs	> 40 deg	> 7000ft	Open

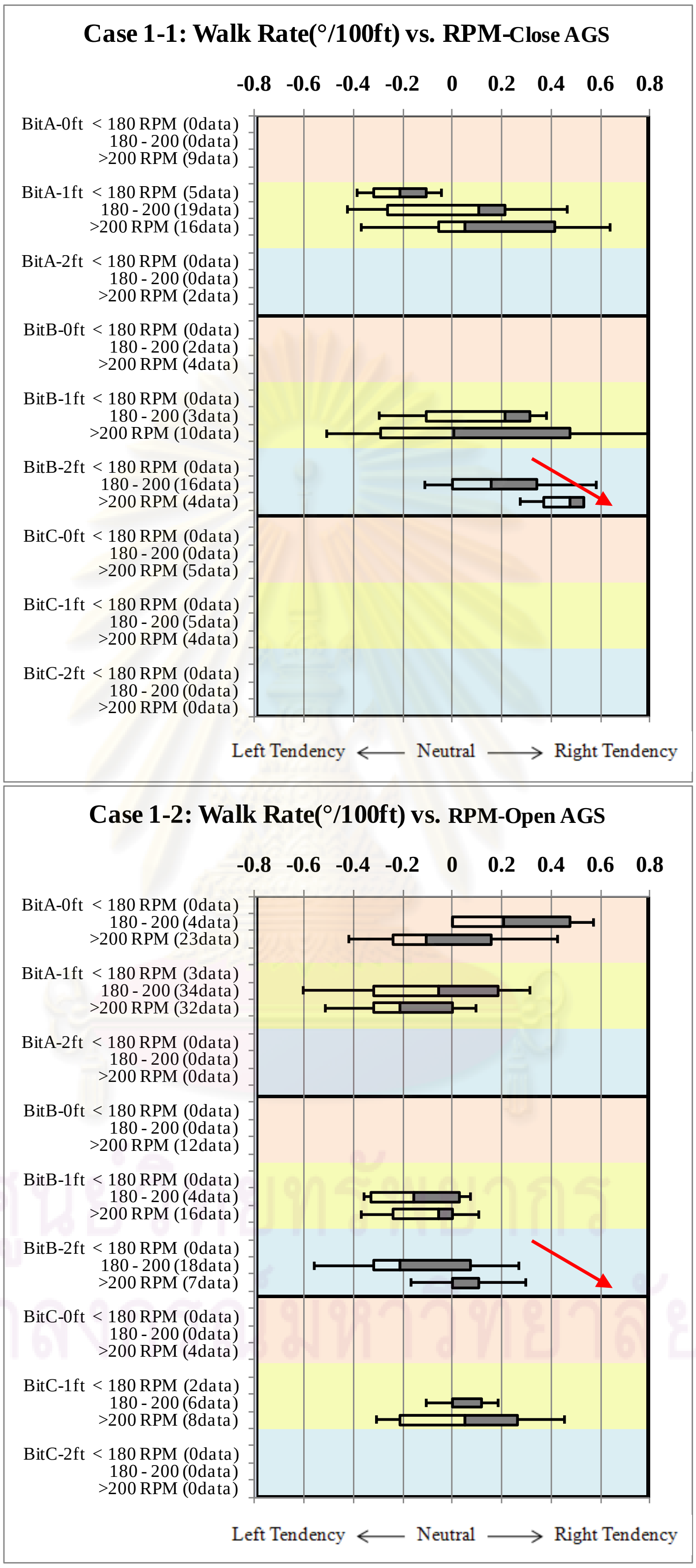


Figure 4-34: Relationship of RPM vs. walk rate. Case1 (hole angle < 30 deg, TVD 5,000-7,000ft).

From Figure 4-34 Case1, Bit-B with 2ft extension walked more to the right when RPM > 200 (red arrow).

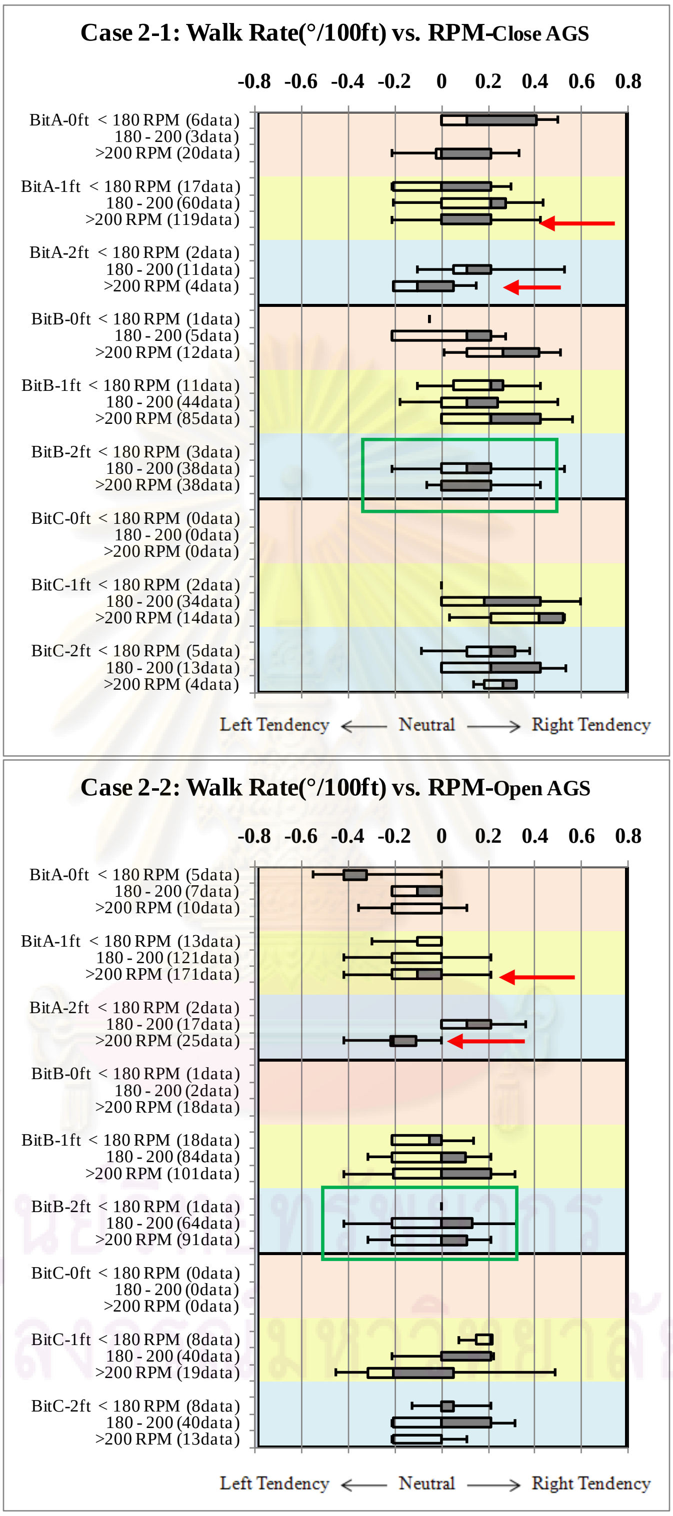


Figure 4-35: Relationship of RPM vs. walk rate. Case2 (hole angle 30-40 deg, TVD 5,000-7,000ft).

From Figure 4-35 Case2, Bit-A with 1ft and 2ft extension walked more to the left when RPM > 200 (red arrow). Bit-B with 2ft had neutral tendency and showed less dispersion in walk rate when increasing the RPM (green rectangular).

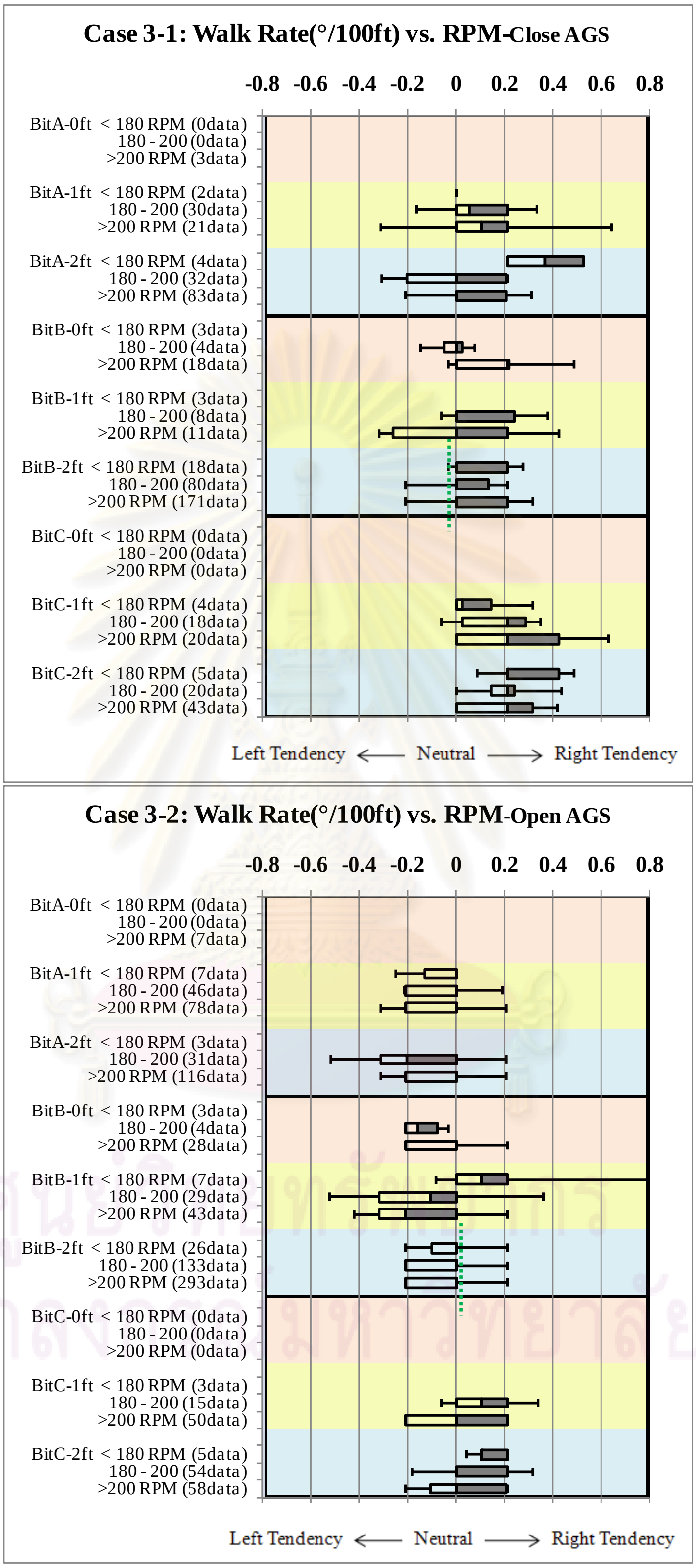


Figure 4-36: Relationship of RPM vs. walk rate. Case3 (hole angle > 40 deg, TVD 5,000-7,000ft).

From Figure 4-36 Case3, Bit-B with 2ft had neutral tendency at any RPM (green dash line).

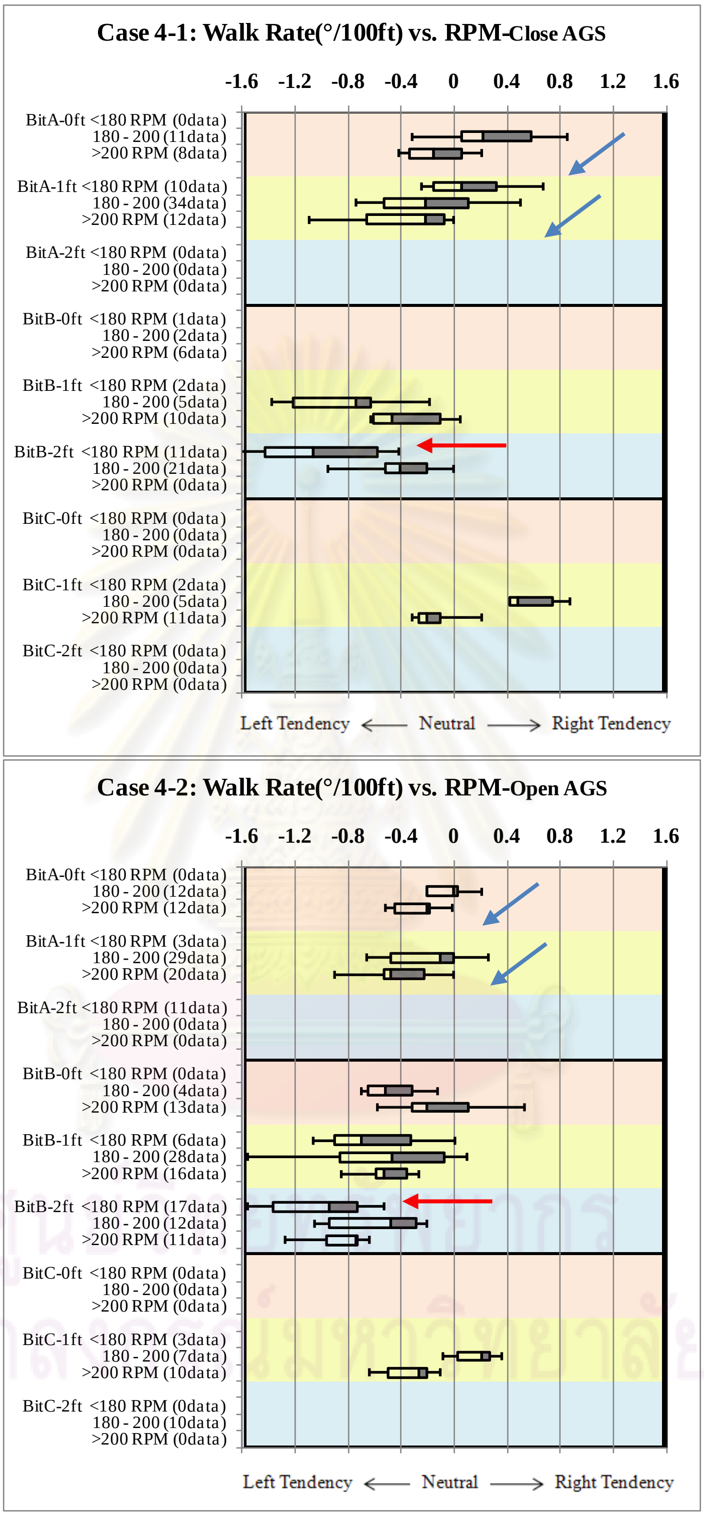


Figure 4-37: Relationship of RPM vs. walk rate. Case4 (hole angle < 30 deg, TVD > 7,000 ft).

From Figure 4-37 Case4, Bit-A with 0ft and 1ft extension walked more to the left when RPM increased (blue arrow) while Bit-B with 2ft extension walked more to the left when RPM < 180 (red arrow).

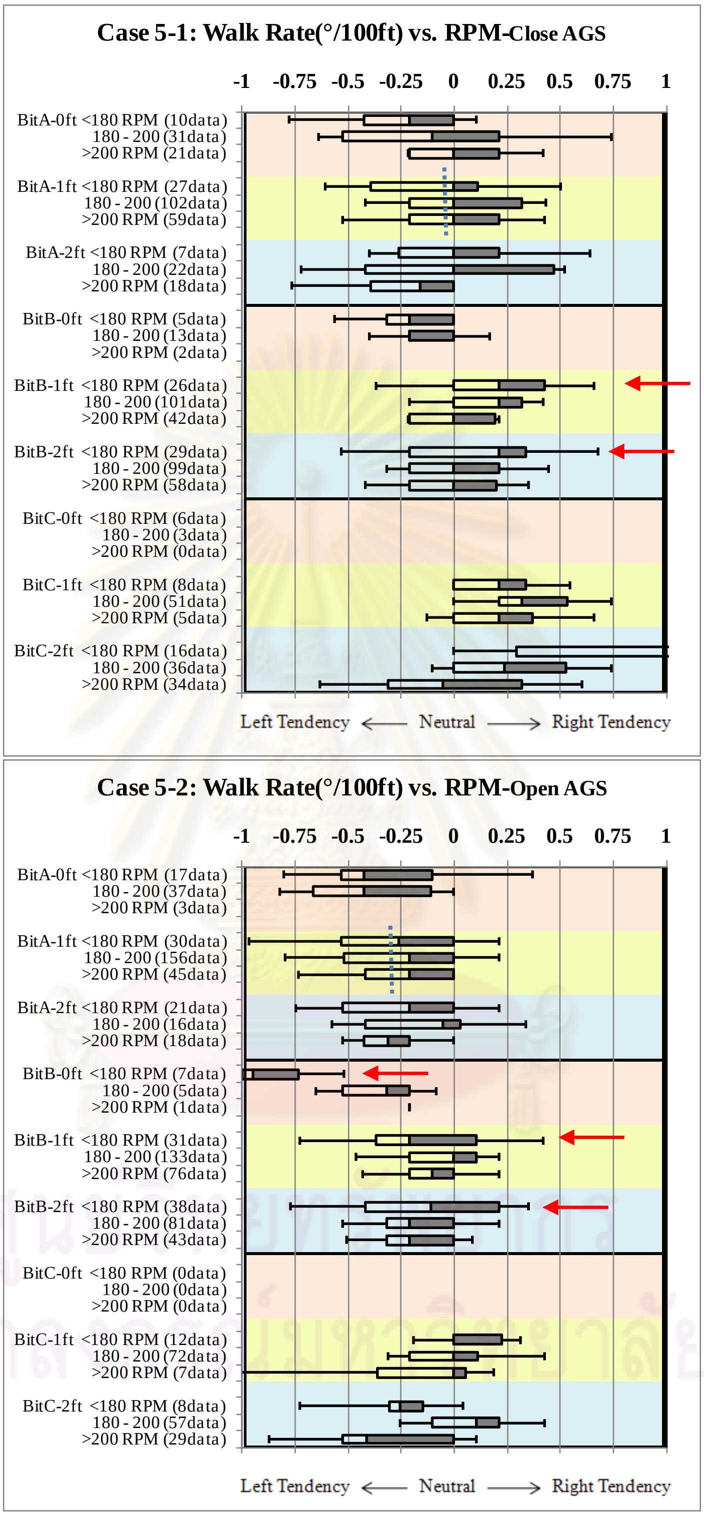


Figure 4-38: Relationship of RPM vs. walk rate. Case5 (hole angle 30-40 deg, TVD > 7,000 ft).

From Figure 4-38 Case5, Bit-A with 1ft extension, the walk rate was constant with any RPM (blue dash line) and Bit-B, there was high dispersion in walk rate when RPM < 180 (red arrow).

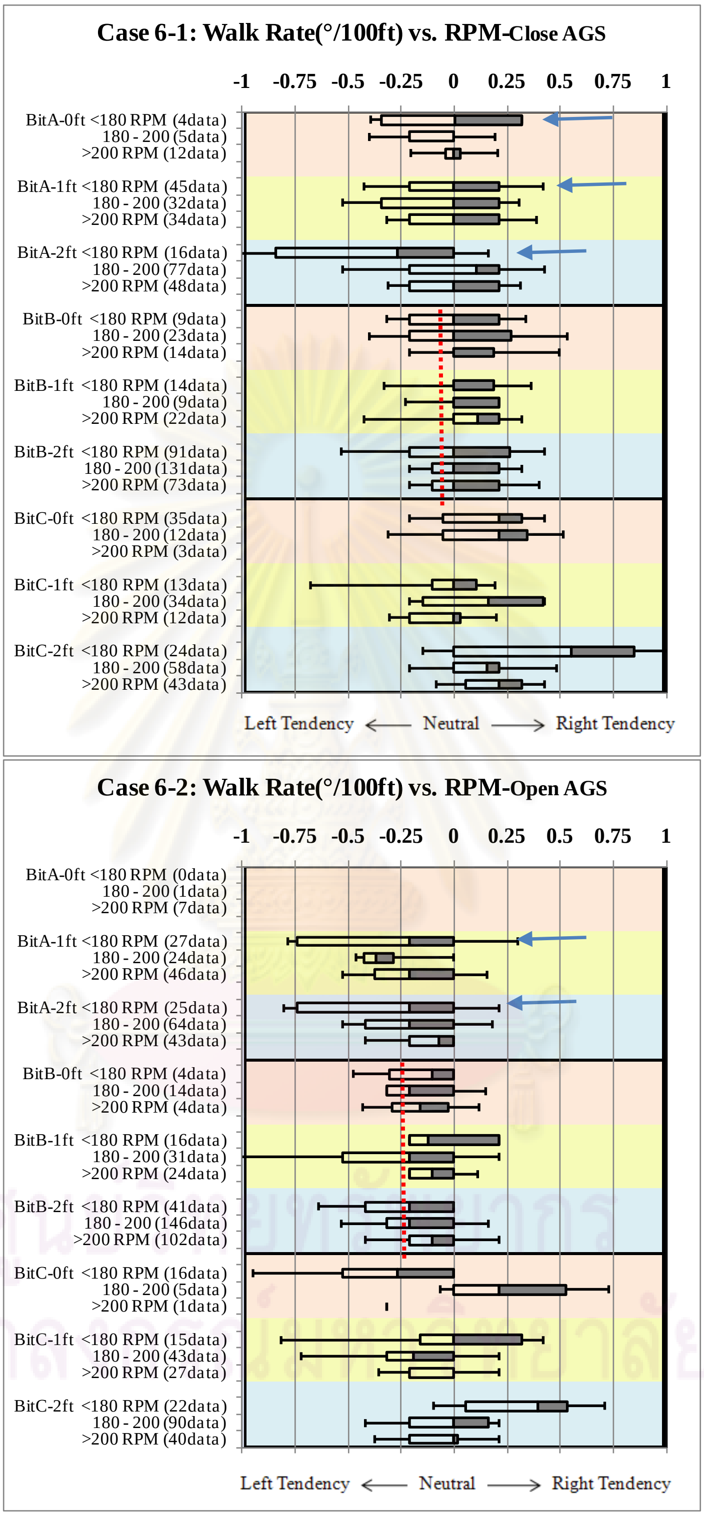


Figure 4-39: Relationship of RPM vs. walk rate. Case6 (hole angle > 40 deg, TVD > 7,000ft).

From Figure 4-39 Case6, Bit-A had high dispersion when RPM < 180 (blue arrow) and Bit-B had very constant walk rate with any RPM (red dash line) evidenced by having similar median walk rate.

From results of every RPM scenario, it could be concluded that the RPM had effect on the walk rate. Changing RPM caused the change in average walk rate ranging from 0 to 0.7 deg/100ft or an average of 0.19 deg/100ft. However the relationships between RPM and walk rate were not linear. There were observations of their relationships as following:

1) At hole angle < 30 deg, TVD 5,000-7,000 ft, Bit-B with 2ft extension walked more to the right when RPM > 200.
2) At hole angle 30-40 deg, TVD 5,000-7,000 ft, Bit-A with 1ft and 2ft extension walked more to the left when RPM > 200. Bit-B with 2ft had neutral tendency and showed less dispersion in walk rate when increasing the RPM.
3) At hole Angle > 40 deg, TVD 5,000-7,000 ft, Bit-B with 2ft had neutral tendency at any RPM
4) At hole angle < 30 deg, TVD > 7,000 ft, Bit-A with 0ft and 1ft extension walked more to the left when RPM increased while Bit-B with 2ft extension walked more to the left when RPM < 180.
5) At hole angle 30 – 40 deg, TVD > 7,000 ft, Bit-A with 1ft extension, the walk rate was constant with any RPM and Bit-B, there was high dispersion in walk rate when RPM < 180.
6) At hole angle > 40 deg, TVD > 7,000 ft, Bit-A had high dispersion when RPM < 180 and Bit-B had very constant walk rate with any RPM.

4.4.7 WOB vs. walk rate

The walk rate of nine BHA configurations in six case of hole angle and TVD with constrained RPM & WOB and two setting of AGS were presented. The constraints for studying the effect of WOB to walk rate was shown in Table 4-21 and the results from every scenario were presented in Figure 4-40 to Figure 4-46.

Table 4-21: Constraints for studying the effect of WOB to walk rate

	RPM	Inc	TVD	AGS
Case1-1	180-200	< 30 deg	5000-7000ft	Close
Case1-2	180-200	< 30 deg	5000-7000ft	Open
Case2-1	180-200	30-40 deg	5000-7000ft	Close
Case2-2	180-200	30-40 deg	5000-7000ft	Open
Case3-1	180-200	> 40 deg	5000-7000ft	Close
Case3-2	180-200	> 40 deg	5000-7000ft	Open
Case4-1	180-200	< 30 deg	> 7000ft	Close
Case4-2	180-200	< 30 deg	> 7000ft	Open
Case5-1	180-200	30-40 deg	> 7000ft	Close
Case5-2	180-200	30-40 deg	> 7000ft	Open
Case6-1	180-200	> 40 deg	> 7000ft	Close
Case6-2	180-200	> 40 deg	> 7000ft	Open

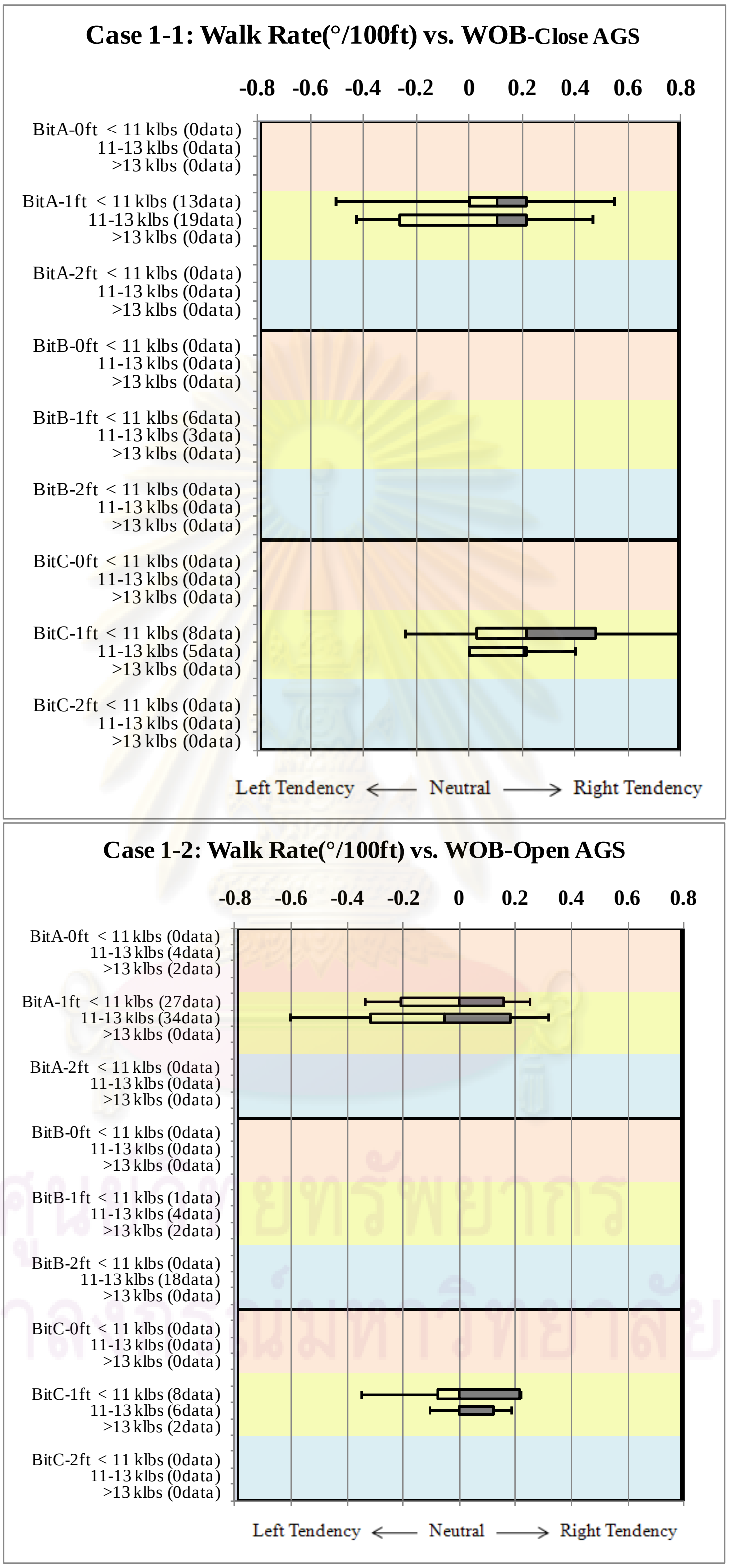


Figure 4-40: Relationship of WOB vs. walk rate. Case1 (hole angle < 30 deg, TVD 5000-7000ft).

There was no discussion of Case1 in Figure 4-40 because the data points were limited.

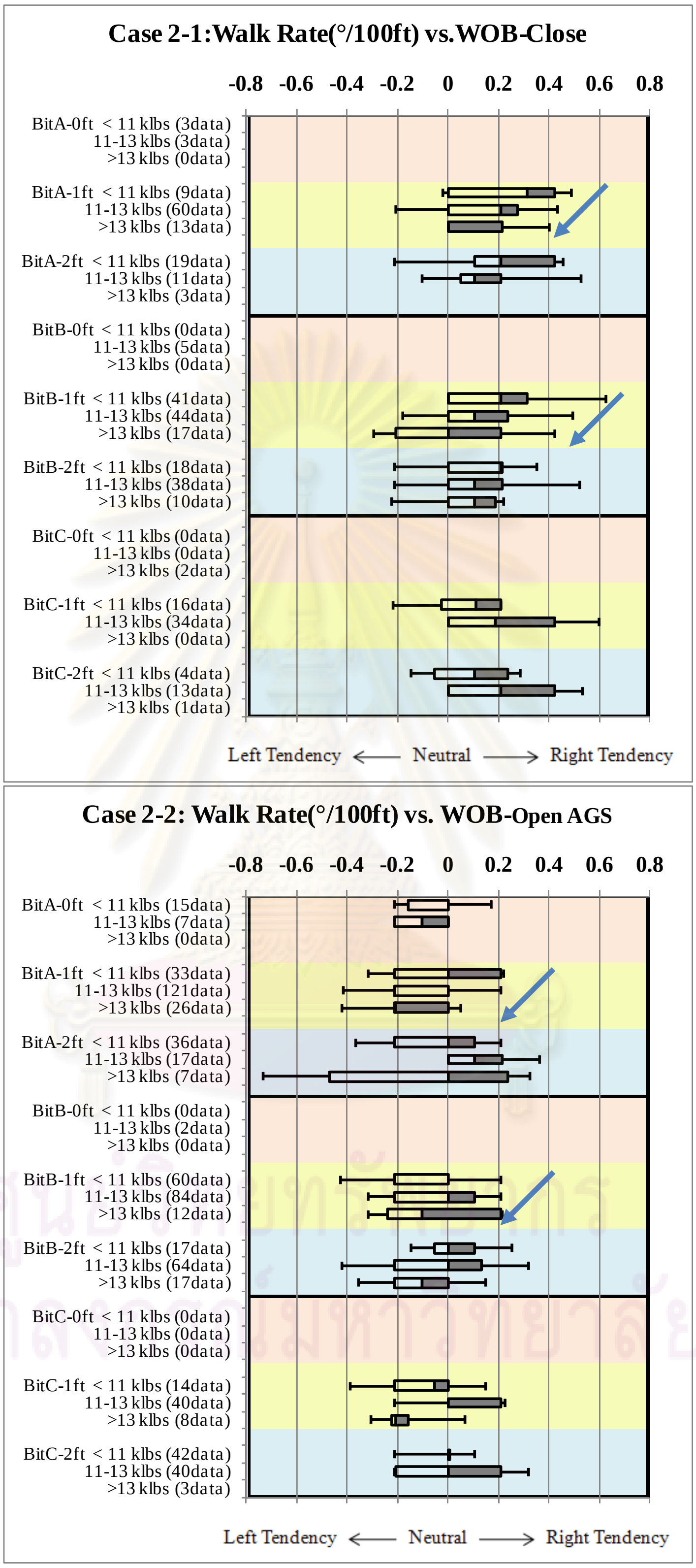
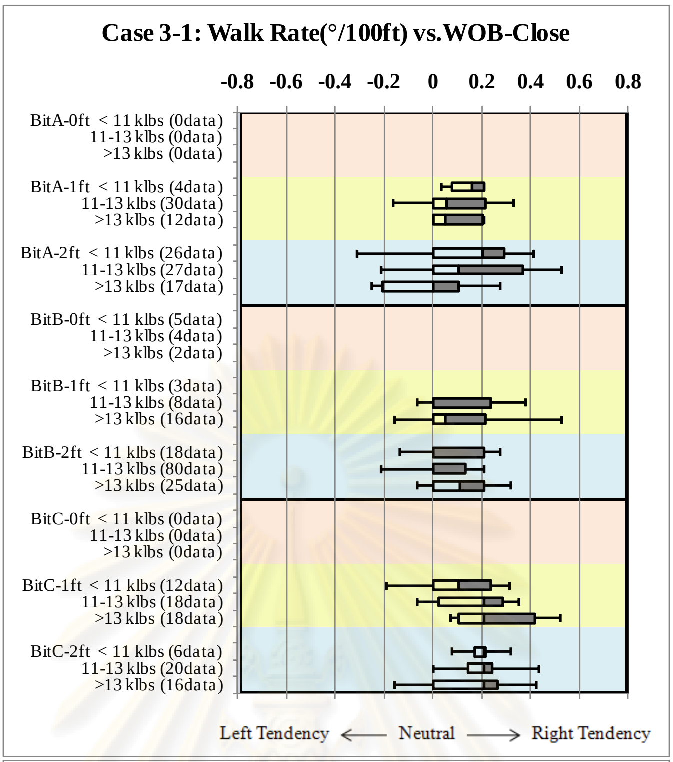


Figure 4-41: Relationship of WOB vs. walk rate, Case2(hole angle 30-40 deg, TVD 5000-7000ft).

From Figure 4-41 Case 2, Bit-A & Bit-B with 1ft extension walked more to the left when increasing WOB (blue arrow).



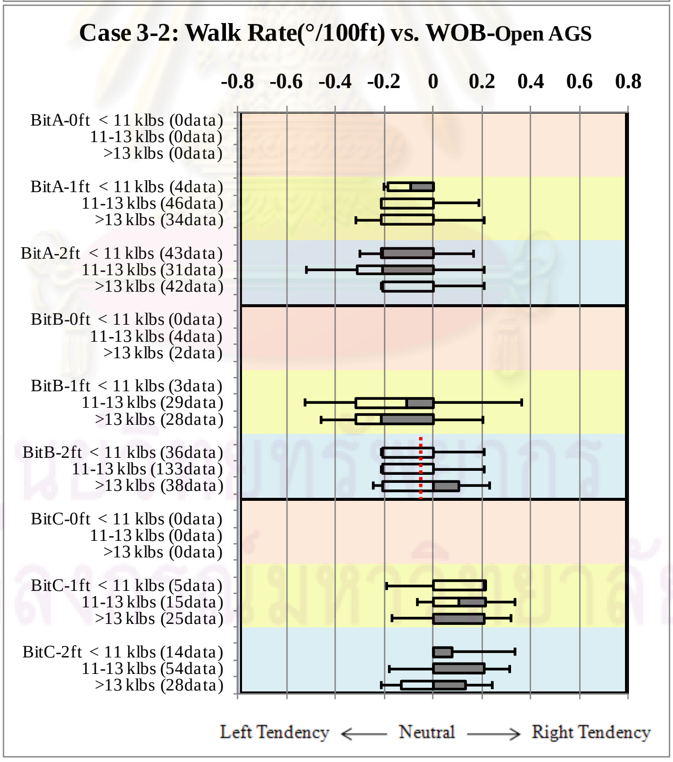


Figure 4-42: Relationship of WOB vs. walk rate, Case3 (hole angle > 40 deg, TVD 5000-7000ft).

From Figure 4-42 Case3, Bit-B with 2ft extension had very minimum effect on walk rate when increasing the WOB (red dash line).

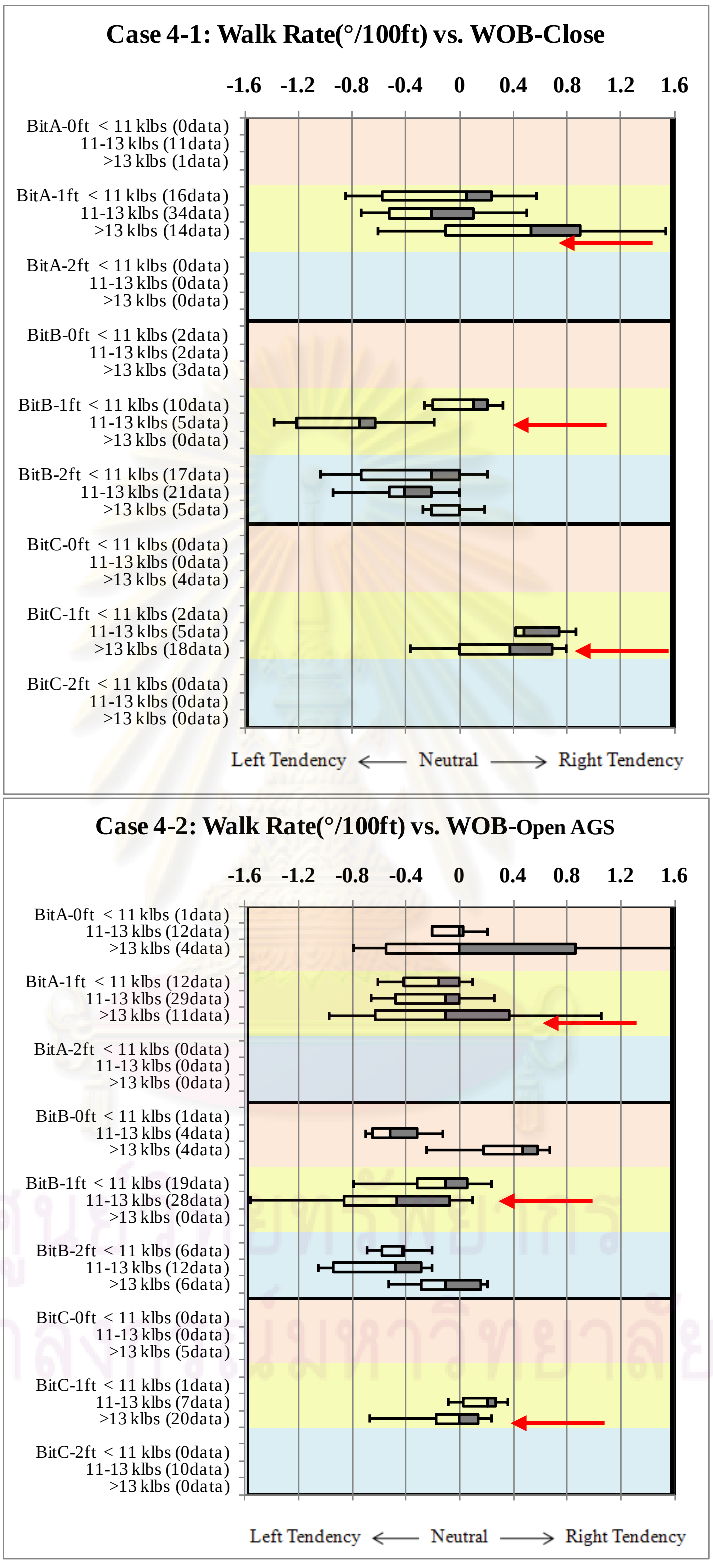


Figure 4-43: Relationship of WOB vs. walk rate, Case4 (hole angle < 30 deg, TVD > 7,000 ft).

From Figure 4-43 Case4, BHA with 1ft extension had more disperse in walk rate when increasing the WOB (red arrow).

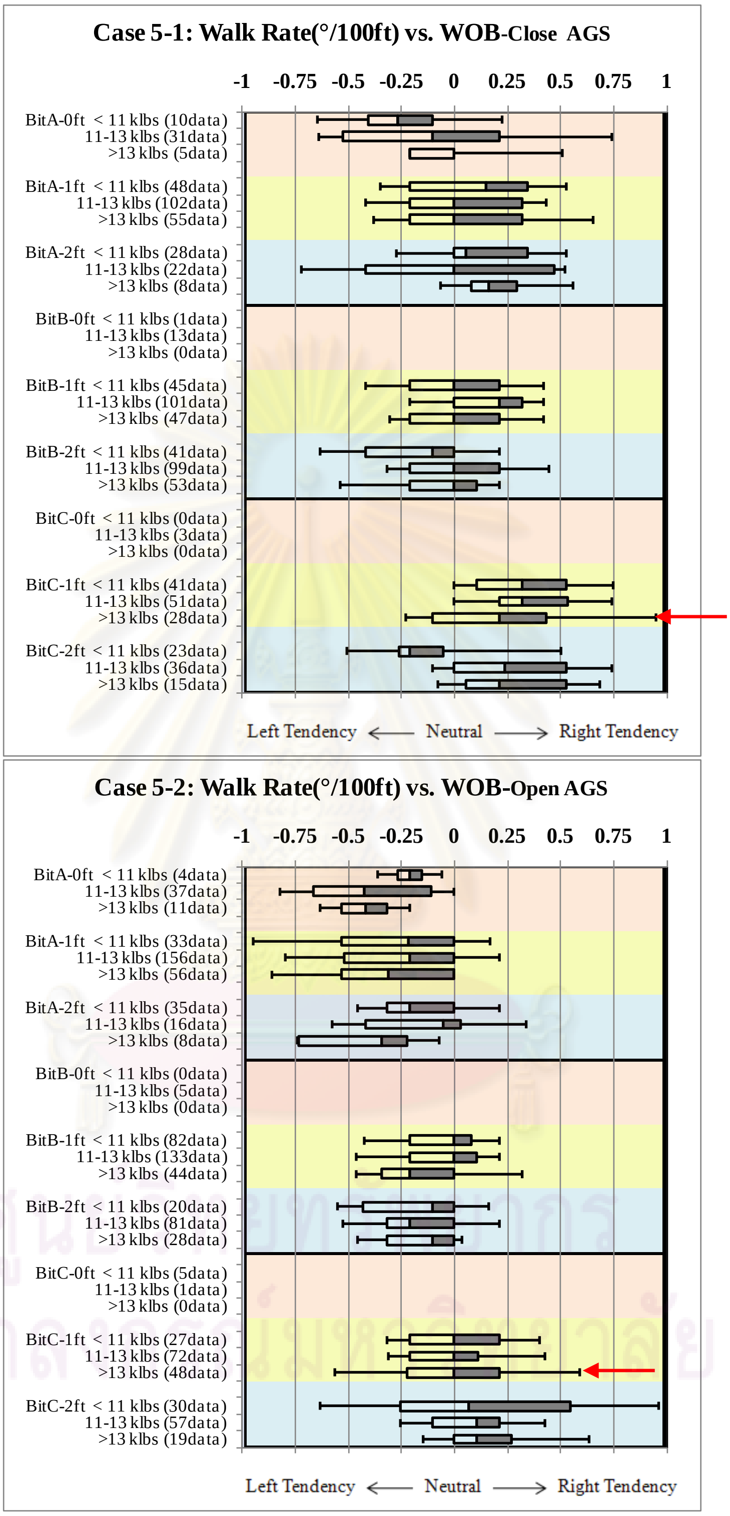


Figure 4-44: Relationship of WOB vs. walk rate, Case5 (hole angle < 30 deg, TVD > 7,000 ft).

From Figure 4-44 Case 5, Bit-C with 1ft extension had large dispersion when WOB > 13 klbs (red arrow).

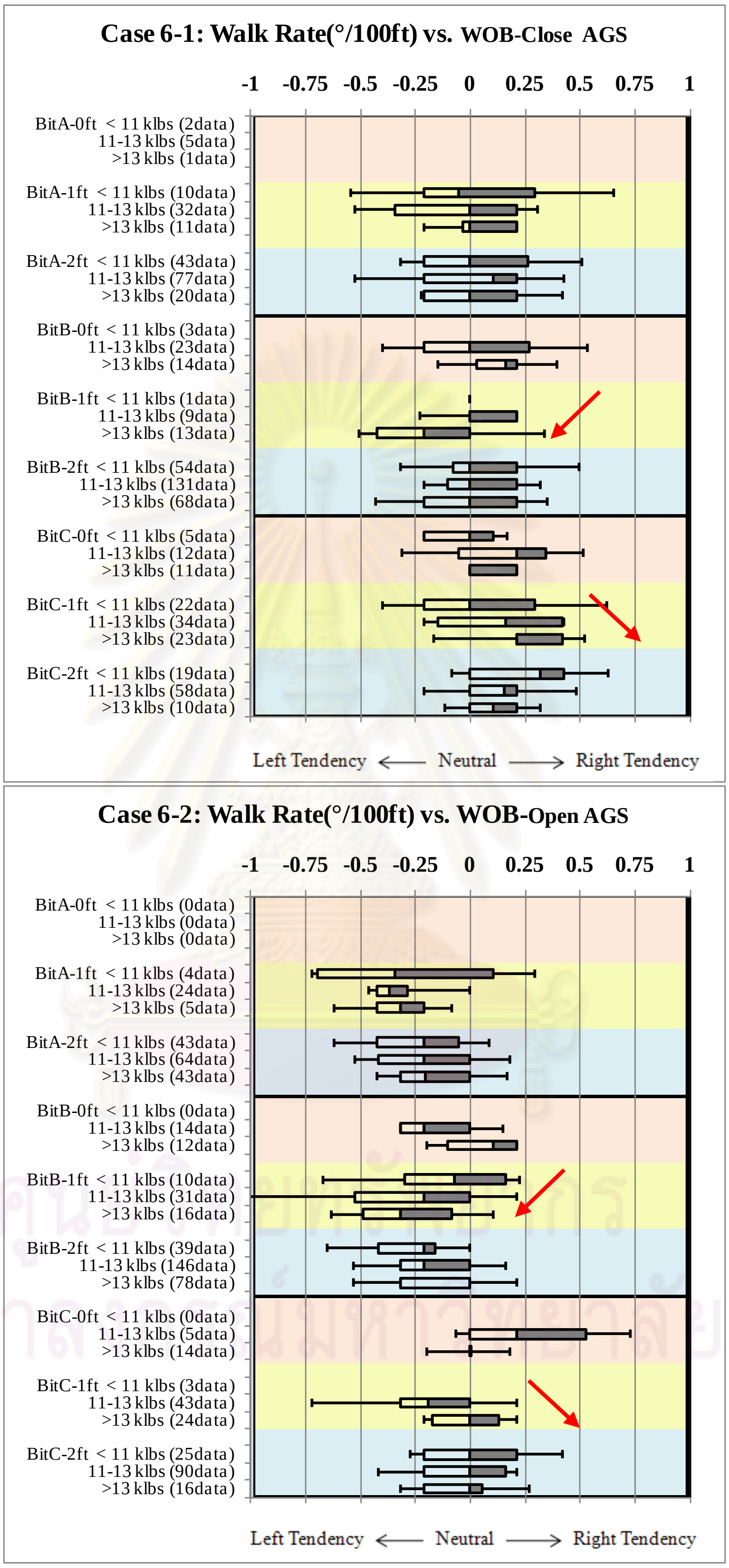


Figure 4-45: Relationship of WOB vs. walk rate, Case6 (hole angle 30-40 deg, TVD > 7,000 ft).

From Figure 4-45 Case6, BHA with 1ft extension, when increasing WOB, Bit-B walked more to the left while Bit-C walked more to the right (red arrow).

From results of every WOB scenario, it could be concluded that the WOB had effect on the walk rate. Changing WOB caused the change in average walk rate ranging from 0 to 1 deg/100ft or an average of 0.175 deg/100ft. However the relationships between WOB and walk rate were not linear. There were observations of their relationships as following:

1) At hole angle 30-40 deg, TVD 5,000-7,000 ft, 1 ft extension, Bit-A and Bit-B walked more to the left when increasing WOB.
2) At hole Angle > 40 deg, TVD 5,000-7,000 ft, Bit-B with 2ft extension had very minimum effect on walk rate when increasing the WOB.
3) At hole angle < 30 deg, TVD > 7,000 ft, BHA with 1ft extension had more disperse in walk rate when increasing the WOB.
4) At hole angle 30-40, TVD > 7,000 ft, Bit-C with 1ft extension had larger dispersion when WOB > 13 klbs.
5) At hole angle > 40 deg, TVD 7,000 ft, BHA with 1ft extension, when increasing WOB, Bit-B walked more to the left while Bit-C walked more to the right.

4.4.8 Result summary and discussion

Relationships between each parameter and walk rate had been established with other parameters constrained. It could be concluded from every scenario that:

1) Every parameter appeared to have an effect to the walk rate. However their relationships were not linear but instead they were different from case to case except for the AGS setting that 97% of the scenarios the AGS with close position have more right hand walk than the AGS in open position.

2) Bit-C had more right hand walk tendency compared to Bit-A and Bit-B.

3) Walk rate had high dispersion when hole angle < 30 deg, however the relationship between walk rate/walk direction and hole angle could not be strongly established since they varied from case to case.

4) Walk rate had more dispersion when TVD was deeper, however it could not concluded on the direction of bit walk since they varied from case to case.

5) The relationships between walk rate and extension length, RPM, WOB were not linear. They varied from case to case.

6) To rank which factors affect most to the walk rate, the change in walk rate from changing of each parameter were summarized. The effect to the walk rate could be ranked as bit model, hole angle, AGS settings, RPM, WOB, extension length and TVD depth at the average values of 0.26, 0.24, 0.20, 0.19, 0.18, 0.161 and 0.160 deg/100ft respectively.

4.5 Walk rate prediction table and recommended parameter table

4.5.1 Walk rate prediction table

Walk rate prediction table was created using the median walk rate for the nine BHA configurations, six cases of hole angle and TVD with constrained RPM & WOB, and two cases of AGS setting. The constraints for walk rate prediction were shown in Table 4-22 and walk rate prediction tables were presented in Table 4-23.

Table 4-22: Constraints for walk rate prediction

	RPM	WOB	Inc	TVD	AGS
Case1-1	180-200	11-13 klbs	< 30 deg	5000-7000ft	Close
Case1-2	180-200	11-13 klbs	< 30 deg	5000-7000ft	Open
Case2-1	180-200	11-13 klbs	30-40 deg	5000-7000ft	Close
Case2-2	180-200	11-13 klbs	30-40 deg	5000-7000ft	Open
Case3-1	180-200	11-13 klbs	> 40 deg	5000-7000ft	Close
Case3-2	180-200	11-13 klbs	> 40 deg	5000-7000ft	Open
Case4-1	180-200	11-13 klbs	< 30 deg	> 7000ft	Close
Case4-2	180-200	11-13 klbs	< 30 deg	> 7000ft	Open
Case5-1	180-200	11-13 klbs	30-40 deg	> 7000ft	Close
Case5-2	180-200	11-13 klbs	30-40 deg	> 7000ft	Open
Case6-1	180-200	11-13 klbs	> 40 deg	> 7000ft	Close
Case6-2	180-200	11-13 klbs	> 40 deg	> 7000ft	Open

Table 4-23: Walk rate prediction table

Case1: Hole Angle < 30deg, TVD 5,000 -7,000 ft		
Extension	AGS-close	AGS-open
0 ft 0 ft		Bit-A: +0.21 / 100ft
1 ft 1 ft	Bit-A: +0.11 / 100ft Bit-C: +0.21 / 100ft	Bit-A: -0.05 / 100ft Bit-B: -0.16 / 100ft Bit-C: 0.00 / 100ft
2 ft	Bit-B: +0.16 / 100ft	Bit-B: -0.21 / 100ft

Case4: Hole Angle < 30deg, TVD > 7,000 ft		
Extension	AGS-close	AGS-open
0 ft 0 ft	Bit-A: +0.21 / 100ft	Bit-A: 0.00 / 100ft Bit-B: -0.52 / 100ft
1 ft 1 ft	Bit-A: -0.21 / 100ft Bit-B: -0.74 / 100ft Bit-C: +0.48 / 100ft	Bit-A: -0.11 / 100ft Bit-B: -0.47 / 100ft Bit-C: +0.21 / 100ft
2 ft	Bit-B: -0.41 / 100ft	Bit-B: -0.47 / 100ft Bit-C: -0.21 / 100ft

Case2: Hole Angle 30-40 deg, TVD 5,000 -7,000 ft		
Extension	AGS-close	AGS-open
0 ft	Bit-B: +0.11 / 100ft	Bit-A: -0.10 / 100ft
1 ft	Bit-A: +0.21 / 100ft Bit-B: +0.11 / 100ft Bit-C: +0.19 / 100ft	Bit-A: 0.00 / 100ft Bit-B: 0.00 / 100ft Bit-C: 0.00 / 100ft
2 ft	Bit-A: +0.11 / 100ft Bit-B: +0.11 / 100ft Bit-C: +0.21 / 100ft	Bit-A: +0.11 / 100ft Bit-B: 0.00 / 100ft Bit-C: 0.00 / 100ft

Case5: Hole Angle 30-40 deg, TVD > 7,000 ft		
Extension	AGS-close	AGS-open
0 ft	Bit-A: -0.11 / 100ft Bit-B: -0.21 / 100ft	Bit-A: -0.43 / 100ft Bit-B: -0.32 / 100ft
1 ft	Bit-A: 0.00 / 100ft Bit-B: +0.21 / 100ft Bit-C: +0.32 / 100ft	Bit-A: -0.21 / 100ft Bit-B: 0.00 / 100ft Bit-C: 0.00 / 100ft
2 ft	Bit-A: 0.00 / 100ft Bit-B: 0.00 / 100ft Bit-C: +0.24 / 100ft	Bit-A: -0.05 / 100ft Bit-B: -0.21 / 100ft Bit-C: +0.10 / 100ft

Case3: Hole Angle > 40 deg, TVD 5,000 -7,000 ft		
Extension	AGS-close	AGS-open
0 ft	Bit-B: 0.00 / 100ft	Bit-B: -0.16 / 100ft
1 ft	Bit-A: +0.06 / 100ft Bit-B: 0.00 / 100ft Bit-C: +0.21 / 100ft	Bit-A: 0.00 / 100ft Bit-B: -0.11 / 100ft Bit-C: +0.11 / 100ft
2 ft	Bit-A: 0.00 / 100ft Bit-B: 0.00 / 100ft Bit-C: +0.21 / 100ft	Bit-A: -0.21 / 100ft Bit-B: 0.00 / 100ft Bit-C: 0.00 / 100ft

Case6: Hole Angle > 40 deg, TVD > 7,000 ft		
Extension	AGS-close	AGS-open
0 ft	Bit-A: 0.00 / 100ft Bit-B: 0.00 / 100ft Bit-C: +0.21 / 100ft	Bit-B: -0.21 / 100ft Bit-C: +0.21 / 100ft
1 ft	Bit-A: 0.00 / 100ft Bit-B: 0.00 / 100ft Bit-C: +0.16 / 100ft	Bit-A: -0.37 / 100ft Bit-B: -0.21 / 100ft Bit-C: -0.19 / 100ft
2 ft	Bit-A: +0.10 / 100ft Bit-B: 0.00 / 100ft Bit-C: +0.16 / 100ft	Bit-A: -0.21 / 100ft Bit-B: -0.21 / 100ft Bit-C: 0.00 / 100ft

The predicted walk rates that more than 0.3 deg/100ft in both directions were marked with red and blue. With these walk rate values, BHA has high tendency to walk outside the target zone. The walk rates with large dispersion (P75 – P25 > 0.5 deg/100ft) were shaded with orange. With large walk rate dispersion, the walk rate tendency is less predictable or has high chance to be different from predicted walk rate value.

The walk rate prediction table can be used as the guideline for bit and BHA selection. From the values in the table, following BHA configurations are recommended from their neutral walk tendencies and low walk rate dispersions; 1)

Bit-B with 1ft or 2ft extension is recommended for well with 30 – 40 deg inclination. 2) BHA with 2ft extension is recommended for well with inclination > 40 deg. The BHA recommendation was based on that the predicted walk rate values were less than 0.3 deg/100ft throughout different TVD depths and AGS settings, and that the values were not shaded with orange which were less predictable. The example of how to use this table was presented below.

<u>Example of walk rate prediction table usage</u>

If a well is planned with hole angle < 30 deg, additionally Bit-A with 1ft extension has been selected for drilling. From walk rate prediction table, Table 4-23, Case 1 & 4, the predicted walk rates are as the following:

Case1: Hole Angle < 30deg, TVD 5,000 -7,000 ft		
Ext	AGS-close	AGS-open
1 ft	Bit-A: +0.11 / 100ft	Bit-A: -0.05 / 100ft

Case4: Hole Angle < 30deg, TVD > 7,000 ft		
Ext	AGS-close	AGS-open
1 ft	Bit-A: -0.21 / 100ft	Bit-A: -0.11 / 100ft

If the well is planed with 50% AGS in close position, then predicted walk rate when TVD 5,000-7,000 ft = (+0.11 -0.05)/2 = 0.03 deg/100ft and predicted walk rate when TVD > 7,000 ft = (-0.21 – 0.11)/2 = 0.16 deg/100ft. And it can be noted that the actual walk rate value has high chance to be different from the predicted value, because the predicted value has high dispersion as shaded with orange.

4.5.2 Recommended parameters for walk rate control

The recommended parameter table for walk rate control was created using the median walk rate for the AGS setting, RPM and WOB that had the most right and left tendency for four BHA configurations, four cases of hole angle and TVD. Table 4-24 presented the recommended parameters for walk rate control which can be used as a guideline for the walk rate correction. When drilling and the desired walk rate are not acquired, this recommended parameters in the table can be used as a guideline in varying surface parameters or changing the setting of AGS to control the walk tendency. The delta walk rate that can be achieved from changing from 180 -200 RPM and 11-13 klbs to the recommended parameters is also provided.

Table 4-24: Recommended parameters for walk rate control

Case2: Hole Angle 30-40 deg, TVD 5,000 -7,000 ft							
Extension	Bit	Most Right: Close AGS		delta walk rate (deg/100ft)	Most Left: Open AGS		delta walk rate (deg/100ft)
1 ft	Bit-A	RPM 180 - 200	WOB < 11 klbs	0.11	RPM > 200	WOB < 11 klbs	-0.21
	Bit-B	RPM < 180	WOB < 11 klbs	0.11	RPM 180 - 200	WOB > 13 klbs	-0.11
	Bit-C	RPM > 200	WOB 11-13 klbs	0.23	RPM 180 - 200	WOB > 13 klbs	-0.21
2 ft	Bit-A		WOB < 11 klbs	0.10	RPM > 200	WOB 11-13 klbs	-0.32
	Bit-B	RPM 180 - 200	WOB < 11 klbs	0.10	RPM 180 - 200	WOB > 13 klbs	-0.11
	Bit-C	RPM > 200		0.06			

Case5: Hole Angle 30-40 deg, TVD > 7,000 ft							
Extension	Bit	Most Right: Close AGS		delta walk rate (deg/100ft)	Most Left: Open AGS		delta walk rate (deg/100ft)
1 ft	Bit-A	RPM 180 - 200	WOB < 11 klbs	0.15	RPM > 200	WOB < 11 klbs	-0.42
	Bit-B	RPM < 180			RPM > 200	WOB > 13 klbs	-0.21
	Bit-C		WOB < 11 klbs	0.05	RPM > 200		
2 ft	Bit-A	RPM < 180	WOB < 11 klbs	0.11	RPM 180 - 200	WOB > 13 klbs	-0.21
	Bit-B	RPM < 180	WOB 11-13 klbs	0.21	RPM > 200	WOB > 13 klbs	-0.32
	Bit-C	RPM < 180	WOB 11-13 klbs	0.29	RPM > 200	WOB 11-13 klbs	-0.52

Case3: Hole Angle > 40 deg, TVD 5,000 -7,000 ft							
Extension	Bit	Most Right: Close AGS		delta walk rate	Most Left: Open AGS		delta walk rate
1 ft	Bit-A	RPM > 200		0.05	RPM > 200	WOB > 13 klbs	-0.11
	Bit-B	RPM < 180	WOB < 11 klbs	0.21	RPM 180-200	WOB > 13 klbs	-0.11
	Bit-C	RPM > 200		0.00	RPM > 200	WOB > 13 klbs	-0.11
2 ft	Bit-A	RPM < 180	WOB < 11 klbs	0.21			
	Bit-B	RPM 180-200	WOB > 13 klbs	0.11	RPM > 200		
	Bit-C	RPM < 180	WOB 11-13 klbs	0.00	RPM > 200		

Case6: Hole Angle > 40 deg, TVD > 7,000 ft							
Extension	Bit	Most Right: Close AGS		delta walk rate	Most Left: Open AGS		delta walk rate
1 ft	Bit-A	RPM < 180	WOB > 13 klbs	0.16	RPM < 180	WOB > 13 klbs	-0.16
	Bit-B	RPM > 200	WOB 11-13 klbs	0.11	RPM 180 - 200	WOB > 13 klbs	-0.11
	Bit-C	RPM > 200	WOB > 13 klbs	0.16	RPM > 200	WOB < 11 klbs	-0.02
2 ft	Bit-A	RPM > 200	WOB < 11 klbs	0.00	RPM < 180	WOB 11-13 klbs	0.00
	Bit-B	RPM > 200	WOB < 11 klbs	0.11	RPM < 180	WOB 11-13 klbs	0.00
	Bit-C	RPM < 180	WOB > 13 klbs	0.16	RPM > 200	WOB > 13 klbs	-0.10

4.6 Validation

In Chapter 4.4, the walk rate prediction table was created using the median walk rate for the nine BHA configurations, six cases of hole angle and TVD with constrained RPM & WOB, and two cases of AGS setting. At this stage, one well drilled in year 2009 was randomly selected and the average walk rate of this well was calculated and compared to the predicted walk rate to see whether this walk rate prediction table could to be use predicting the actual walk rate. The selected well information was presented in Table 4-25.

Table 4-25: Well information of validation

Bit used	Bit-A
BHA / Extension	1 ft extension
Depth in and out	7,264 - 12,231 ft
TVD in and out	5,029 - 9, 157 ft
Hole angle started and ended	32.4 - 32.3 deg

The hole angle of the selected well was equal to 32 deg, hence the walk rate prediction table Case2 and Case5 from Table 4-24 were used.

Case2: Hole Angle 30-40 deg, TVD 5,000 -7,000 ft			Case5: Hole Angle 30-40 deg, TVD > 7,000 ft		
Extension	AGS-close	AGS-open	Extension	AGS-close	AGS-open
0 ft	Bit-B: +0.11 / 100ft	Bit-A: -0.10 / 100ft	0 ft	Bit-A: -0.11 / 100ft Bit-B: -0.21 / 100ft	Bit-A: -0.43 / 100ft Bit-B: -0.32 / 100ft
1 ft	Bit-A: +0.21 / 100ft Bit-B: +0.11 / 100ft Bit-C: +0.19 / 100ft	Bit-A: 0.00 / 100ft Bit-B: 0.00 / 100ft Bit-C: 0.00 / 100ft	1 ft	Bit-A: 0.00 / 100ft Bit-B: +0.21 / 100ft Bit-C: +0.32 / 100ft	Bit-A: -0.21 / 100ft Bit-B: 0.00 / 100ft Bit-C: 0.00 / 100ft
2 ft	Bit-A: +0.11 / 100ft Bit-B: +0.11 / 100ft Bit-C: +0.21 / 100ft	Bit-A: +0.11 / 100ft Bit-B: 0.00 / 100ft Bit-C: 0.00 / 100ft	2 ft	Bit-A: 0.00 / 100ft Bit-B: 0.00 / 100ft Bit-C: +0.24 / 100ft	Bit-A: -0.05 / 100ft Bit-B: -0.21 / 100ft Bit-C: +0.10 / 100ft

The predicted walk rate and actual walk rate was presented in Table 4-26 and Figure 4-46.

Table 4-26: Predicted walk rate vs. actual walk rate

	TVD 5,000-7,000 ft, AGS close	TVD 5,000-7,000 ft, AGS open	TVD > 7,000 ft, AGS close	TVD > 7,000 ft, AGS open
Predicted walk rate(deg/100ft)	0.21	0.00	0.00	-0.21
Actual walk rate (deg/100ft)	n/a	n/a	0.02	-0.25
Discrepancy (deg/100ft)	n/a	n/a	0.02	-0.04

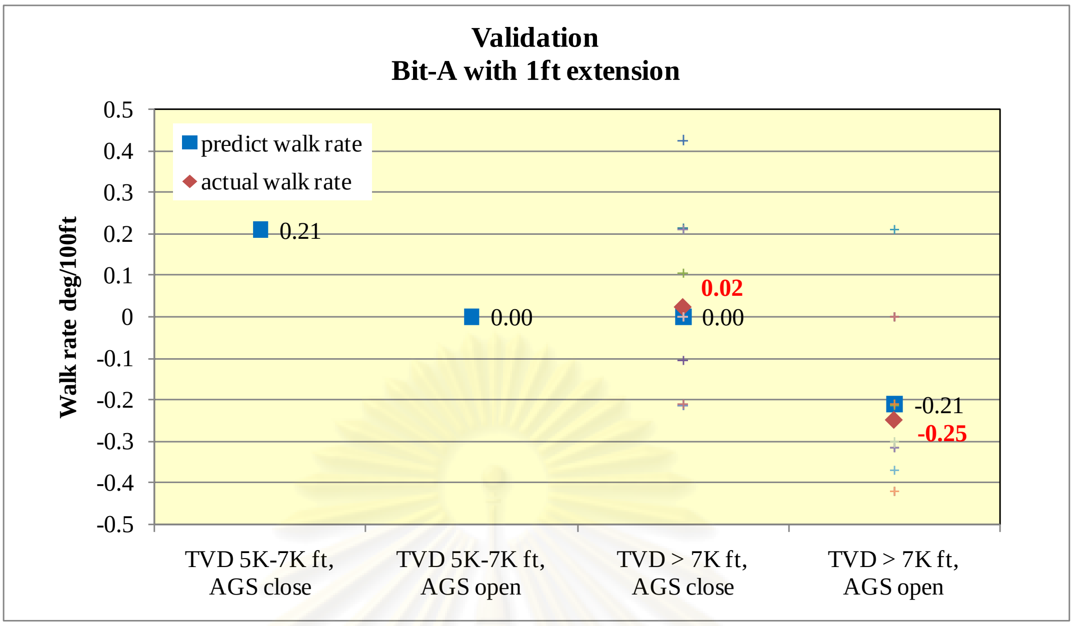


Figure 4-46: Predicted walk rate vs. actual walk rate

For the selected well, there was no data point at TVD 5,000-7,000 ft because the drilling parameters used were not in the range of RPM 180-200 and WOB 11-13 klbs. For TVD > 7,000 ft, predicted walk rate at AGS close and open was equal to 0.00 and -0.21 deg/100ft. These predicted numbers were also shaded with orange which suggesting the high dispersion of walk rate value. Result from validation showed that the actual walk rates equal to 0.02 and -0.25 deg/100ft in AGS close and open which were 0.02 and -0.04 deg/100ft different from predicted walk rate.

From the validation result, the walk rate prediction table could be used effectively to predict the walk rate of the actual well drilled and the discrepancy was less than or equal to 0.04 deg/100ft.

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The objectives of this study were to address the factors that have influence on the bit walk, summarize their effects and create the walk rate prediction table that could be used as a guideline for better pre-job planning. The results from this study could be concluded as follows:

1. From studying the effect of one parameter to the walk rate while not constraining other parameters, the study results indicated that the walk rate was influenced by AGS setting, bit model, hole angle and TVD. The extension length, RPM and WOB did not show considerable effect to the change in walk rate. However from studying the effect of one parameter to the walk rate while constraining other parameters to minimize their influences, the study results indicated that the walk rate was influenced by bit model, hole angle, AGS settings, RPM, WOB, extension length and TVD depth at average values of 0.26, 0.24, 0.20, 0.19, 0.18, 0.161 and 0.160 deg/100ft respectively. From these two methods, first three factors that had influence the bit walk were bit model, hole angle and AGS setting.

2. In addition to the previous studies from Perry and Bennerman, this thesis studied the effect of bit walk from stabilizer size or AGS setting and the results showed that AGS setting was one of the top three factors that affecting bit walk.

3. From studying the effect of one parameter to the walk rate while constraining other parameters, every parameter appeared to have an effect to the walk rate. However their relationships were not linear but instead they varied from case to case except for the AGS setting that 97% of the scenarios the AGS with close position walked more to the right than the AGS in open position.

4. The walk rate prediction table has been created, and from the validation could be used to effectively predict the walk rate with discrepancy less than 0.05 deg/100ft. The walk rate prediction table can be used as the guideline for pre-job

planning such as well planning, BHA design and bit selection to increase the chance of hitting the drilling targets. From walk rate prediction table, following BHA configurations are recommended for the neutral walk tendency and low walk rate dispersion; Bit-B with 1ft or 2ft extension for well with 30 – 40deg inclination, and BHA with 2ft extension for well with inclination > 40 deg.

5. When drilling and the desired walk rate are not acquired, the recommended parameter table can be used as a guideline in varying surface parameters or changing the setting of AGS to control the walk tendency. And if the walk rate correction achieves, hours can be saved from tripping and replacing a new BHA.

5.2 Recommendations

The following points are recommended for the future study:

1. In this study, the rate of azimuth change is the investigative parameter. In order to get more understanding about the relationship, the rate of walk rate change might be included as another investigative parameter.

2. For better pre-job planning, the walk rate prediction table can be used for bit and BHA selection concerning the bit walk. However in the pre-job planning phase, build rate & drop rate is the key for BHA selection therefore for future study, the prediction of build/drop rate for each BHA configuration should be also included as one part of the study.

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VITAE

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