

Sudan-Unity Oil Field Formation Force and Bit Profile Effects on The Well Trajectory

A.A. Ibrahim and ¹T.A. Musa

China University of Geosciences, Wuhan, 430074, China

¹Petroleum Engineering Department, Sudan University of Science and Technology, Khartoum,
P.O. Box 12, Sudan

Abstract: The nature of formation is an important factor to affect the bit trajectory, so that the hole deviation problems are taken place both in straight and directional drilling. To control the bit trajectory satisfactorily, it is necessary to determine not only the "assembly force" by selecting an appropriate bottom hole assembly (BHA) lying in a definite shape of borehole, but also the "formation force" due to the interaction between the bit and the formation. The drillers had long been embarrassed by the difficulty of keeping the hole straight in vertical drilling. Herein, try to calculate the formation forces to change the angles of inclination and azimuth quantitatively at the Unity Oil Field-Sudan.

Key words: Hole deviation, bit profile, bit trajectory, formation forces, angle of inclination, azimuth, rock anisotropy

INTRODUCTION

Many investigators had worked to find out the mechanism of the interaction between the bit and the rock to explain the natural angle-building tendency in crooked region in the past thirty years, but a satisfactory theory is still not available presently. Some proposed theories are only qualitative and others give the quantitative analysis not quite rigorously. Based on field observations, it is generally accepted that the roller cone bits have nearly always a right tendency and most PDC bits have a left tendency. Knapp^[1] emphasized that the azimuthal behavior of the drilling system is influenced by formation characteristics, bit profile, bit size, formation dip, weight on bit (WOB), BHA, and other factors. In analyzing some well trajectories, Su Yiniao^[2] concluded that the bit profile could affect the azimuthal behavior of the BHA.

A bit with a high side cutting ability does not produce necessarily a high rate of inclination on the well trajectory. This rate depends on the side force and weight applied on the bit, on the bit tilt angle and also on the rock formation. Likewise, the azimuthal behavior of a drilling system must not be attributed only to the walk tendency of the bit (Fig. 1).

Some friction phenomenon along the BHA (mainly at stabilizers levels) can greatly influence the azimuthal tendency of the drilling system. At last, the formation effect (rock anisotropy) may be decisive in both the build/drop and azimuth rate of the trajectory.

When the bit drills into hard rock from soft layer, up dip deviation could be formed due to the lower drilling

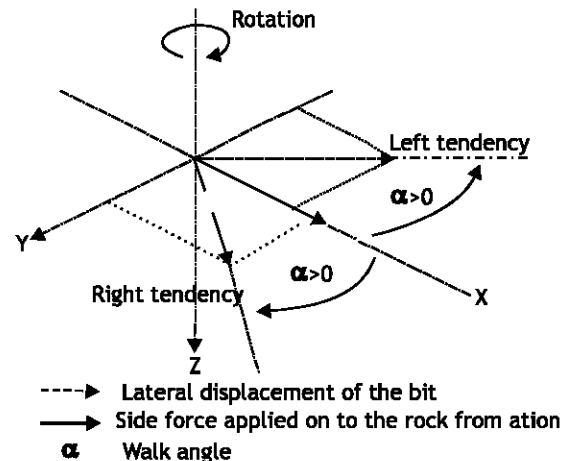


Fig. 1: Definition of the walk angle

rate in hard formation. On the other hand, it predicts down dip when the bit drills into softer rock, which is not quite consistent with the experimental results acquired by Horibe, Deere and Miller (textbook-1992) who had conducted a series of full-scale tests at the Drilling Research Laboratory in Salt Lake City. To decide the effect of formation on the angle building of borehole, Lubinski^[3] (textbook-1992) first introduced the conception of the formation anisotropy index (h), which defined as:

$$h = 1 - \frac{\text{drillability parallele to bedding plane}}{\text{drillability perpendicular to bedding plane}}$$

Then, Murphey and Cheatham^[4] derived the formation force P_a in connection with Lubinsk as Millheim^[5] and others admitted the existence of this force^[6-9] but did not treat it quantitatively.

Basic assumptions

1. The cutting ability of an ideal bit is the same in any direction.
2. The formation force is acting on the plane perpendicular to the strike of the beds.
3. Each stratum of the formation is homogeneous and continuous.
4. The effect of tilt angle of bit is not considered.
5. Rock is in the stage of volume fracture (including surface fracture).
6. The formation force is acting on the plane perpendicular to the strike of the beds.

7. The bit would have a tendency to slide down dip when the included angle between the bit axis and the bedding is small than 40° . Different arrows of $\Delta\phi_1$ and $\Delta\phi_2$ are drawn to show the relative position of hole axis with the formation up dip direction (Fig. 2).

Natural angle building force: Under normal condition of cuttings removal, the penetration rate V of a tri-cone bit is governed by an exponential law as ($1 \leq m < 3$); $V = A P_B^m$. The rock fracture is in the surface stage when the weight on bit P_B is small than a certain value P_{C_0} , called critical weight on bit and the average pressure at the hole bottom F_t is smaller than the compressive strength of rock

σ , that is $\frac{P_B}{F_t} \leq \sigma$ the index ($m = 1$). When P_B is larger than P_C , the rock fracture changes to the volume stage and the index m has a value lying between 1 and $3^{[10]}$.

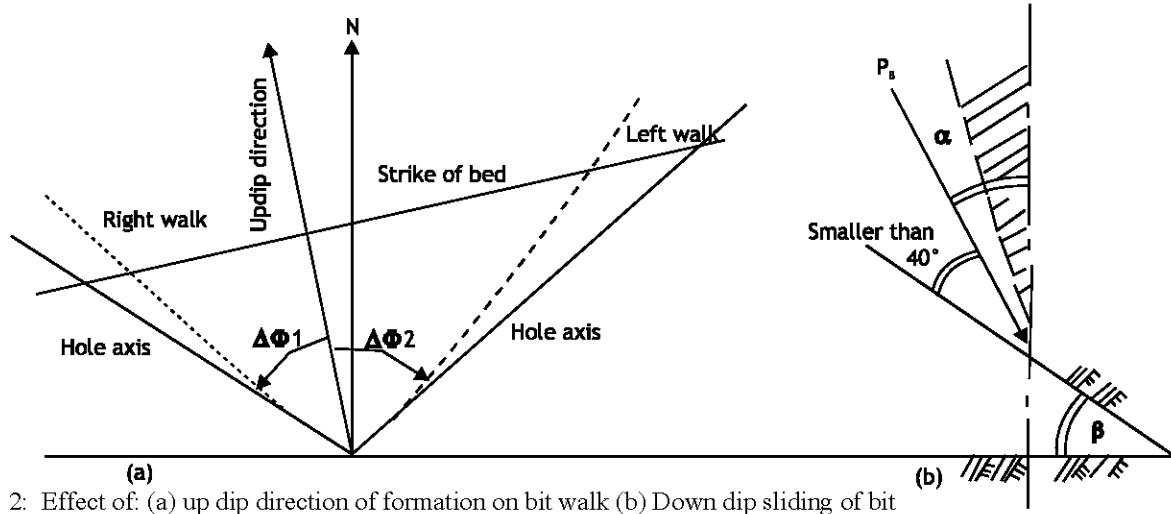


Fig. 2: Effect of: (a) up dip direction of formation on bit walk (b) Down dip sliding of bit

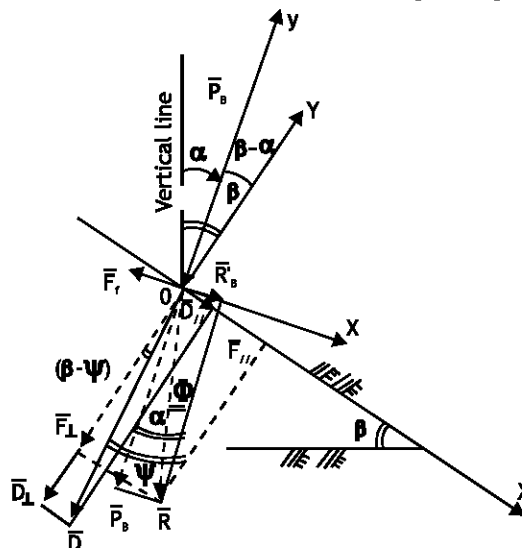


Fig. 3: Forces and displacements in the cross-sectional plane of formation

Surface fracture: In Fig. 3 $\bar{P}_B$ is the weight on bit, $\bar{R}_B$ is the lateral assembly force on wall of well and $\bar{R}$ is their resultant. Besides, F_f is the interactive force between rock and bit due to the dip and anisotropy of the formation.

Let

α is the angle of inclination.

φ is the included angle between resultant force $\bar{R}$ and the vertical line.

$\bar{F}_{//}$ is the component force of $\bar{R}$ parallel to the bedding planes.

$\bar{F}_{\perp}$ is the component force $\bar{R}$ normal to the bedding planes.

$\bar{V}_{//}$ is the cutting speed of bit parallel to the bedding planes.

$\bar{V}_{\perp}$ is the cutting speed of bit normal to the bedding planes.

$\bar{D}_{//}$ is the displacement in a time interval parallel to the bedding planes due to $\bar{V}_{//}$.

$\bar{D}_{\perp}$ is the displacement in the same time interval normal to the bedding planes due to $\bar{V}_{\perp}$.

$\bar{D}$ is the resultant displacement $\bar{D}_{//}$ of and $\bar{D}_{\perp}$.

ψ is the angle of resultant displacement, or the inclined angle between $\bar{D}$ and the vertical line.

In the surface fracture stage, we have

$$\begin{aligned} D_{\perp} &= nF_{\perp} \\ D_{//} &= nh'F_{//} \end{aligned}$$

where n and h' are constant coefficients.

Denotes the index of formation anisotropy, in holding drilling, the inclination remains unchanged and $\bar{F}_f = -\bar{R}'_B$. Then the drilling direction will coincide with that of weight on bit P_B that is $\varphi = \alpha$ and therefore,

$$\frac{\operatorname{tg}(\beta - \alpha)}{\operatorname{tg}(\beta - \varphi)} = 1 - h \quad (1)$$

It can be found that

$$R' = P_B \operatorname{tg}(\alpha - \varphi')$$

so

$$F_f = -P_B \operatorname{tg}(\alpha - \varphi')$$

and

$$\operatorname{tg}(\alpha - \varphi') = \frac{h \operatorname{tg}(\beta - \alpha)}{1 - h + \operatorname{tg}^2(\beta - \alpha)}$$

yields

$$F_f = -\frac{h \operatorname{tg}(\beta - \alpha)}{1 - h + \operatorname{tg}^2(\beta - \alpha)} \cdot P_B \quad (2)$$

The negative sign in the above equations denotes that the direction of the deviation force F_f is opposed to the x-axis in an up dip trend. In fact, is the same as

Merphey-Cheatham formula. That means their formula involves the basic assumptions adopted here. In drilling isotropic rock, $h=0$, which means $\varphi = \varphi'$ then the bit will drill along the direction of the resultant force $\bar{R}$ which is also a conclusion of some investigators for drilling in isotropic formation.

An actual bit has lateral cutting ability alongside the axial penetration, though it is usually smaller than the axial counterpart. To study such an anisotropic property of actual bits, the conceptions of bit cutting index and bit anisotropic index are introduced. In Fig. 4, a tri-cone bit is acted by a force $\bar{P}_{\eta}$. The included angle between it and the bit axis is η . When it drills into an isotropic formation, the penetrating advancement S_{η} along the direction of $\bar{P}_{\eta}$ in unit time is

$$S_{\eta} = nK_{\eta} P_{\eta}^m$$

where: K_{η} is called the bit cutting coefficient.

When the force is acting along the bit axis, $\eta=0$ and the corresponding coefficient K_0 is set to equal one. When the force P is acting along the hole axis and η direction separately, the corresponding penetrating advancements are denoted by $(S_0)p$ and $(S_{\eta})p$, then

$$\frac{(S_{\eta})p}{(S_0)p} = \frac{nK_{\eta} P^m}{nK_0 P^m} = \frac{K_{\eta}}{K_0} = K_{\eta}$$

Let ΔK_{η} denotes the bit an isotropic index that is defined as:

$$\Delta K_{\eta} = 1 - K_{\eta}$$

and K_{90} denotes the transverse cutting index, then the cutting coefficient in any direction can be given as

$$K_{\eta} = \sqrt{(\cos \eta)^{2m} + K_{90}^2 (\sin \eta)^{2m}} \quad (3)$$

The value of K_{90} , determined by experimental measurements, depends on the structures of various types of bits.

Volume fracture: The basic assumptions are still needed. When the rock is in the stage of volume fracture, we have

$$D_{\pm} = nF_{\pm}^m \quad D_{//} = nh'F_{//}^m$$

from Fig. 3

$$\operatorname{tg}(\beta - \psi) = (1 - h) \operatorname{tg}^m(\beta - \varphi')$$

Under the holding condition of steady inclination, $\alpha = \psi$ then from the geometrical relations,

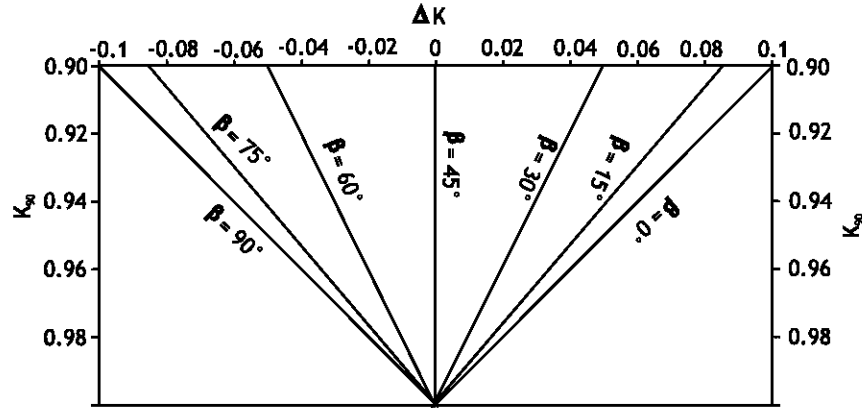


Fig. 5: Relation among ΔK , β and K_{90}

- $(\Delta K + h) > 0$ F_f will cause updip deviation;
 $(\Delta K + h) < 0$ F_f will cause downdip deviation;
 $(\Delta K + h) = 0, F_f = 0$, no deviation will occur at all.

In fact, h is usually a very small positive number (for example $h = 0 \sim 0.075$ according to Lubinski), so that when ($\beta = 60^\circ$, $H = \Delta K + h$) is most probably negative so that F_f will cause down dip deviation and the bit will tend to drill along the bedding planes. When β lies between 55° and 65° , each of the three states explained above may occur. The critical dip angle of formation is so called and denoted by β_c because the deviation will change at this point from up dip to down dip or conversely. Value of β_c , the critical dip angle of formation, can be determined from the following equation

$$\sqrt{c \cos^2 \beta_c + K_{90}^2 \sin^2 \beta_c} - \sqrt{\sin^2 \beta_c + K_{90}^2 \cos^2 \beta_c} + h = 0 \quad (8)$$

And, the critical analysis can prove that $\beta_c \geq 45^\circ$

In directional drilling, line of action of the weight on bit is not lying generally on the bed cross section which is perpendicular to the strike of bed. The cone of weight on bit shown in Fig.6 is an inverted cone generated by the line of action of P_B . Let the length of the generating line denote the magnitude of P_B and the half-cone angle equal to the inclination α . The azimuth difference between P_B and the cross section is demonstrated by $\Delta \phi$. Decompose P_B into, P'_B and P''_B that is $\bar{P}_B = \bar{P}'_B + \bar{P}''_B$, which will create the deviating force $\bar{F}'_f$.

Form the geometrical relation $\bar{P}'_B$ and $\bar{F}'_f$ can be determined as

$$P'_B = \frac{\cos \alpha}{\cos \alpha'} \cdot P_B$$

where: α' is the included angle between $\bar{P}_B$ and the vertical line

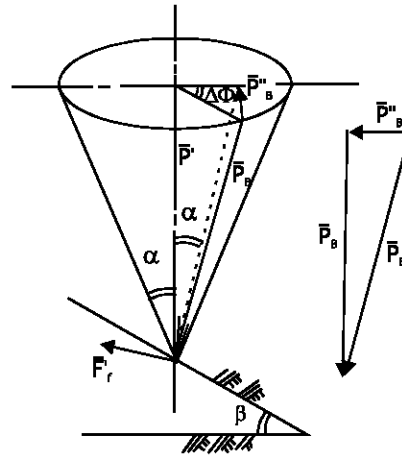


Fig. 6: Cone of weight on bit

$$\alpha' = \tan^{-1} (\tan \alpha \cdot \cos \Delta \phi)$$

$$\text{and} \quad F'_f = \frac{H \tan (\beta - \alpha') \cdot P'_B}{1 - H + \tan^2 (\beta - \alpha')} \quad (9)$$

The phase difference $\Delta \phi$ is $\Delta \phi = \phi_w - \phi_s$ where ϕ_w is the azimuth of borehole. ϕ_s is the up dip azimuth of the dipping strata.

Calculation of combined an isotropic index H: As stated above, the side forces acting on bit to change the inclination are originated from two sources: the bottom hole assembly and the formation. They are P_α and F_α . When these two are numerically equal but opposite in signs, the borehole inclination will hold unchanged. Under such a condition, the combined an isotropic index H can be calculated by

$$H = \frac{P_\alpha [1 + \tan^2 (\beta - \alpha')]}{P_\alpha + P'_B \tan (\beta - \alpha') \cos \Delta \phi'} \quad (10)$$

Table 1: Comparison of computed azimuth changes with actual results

Well	Depth m	Formation (stratified sandstone and mudstone)	up dip direction of strata deg	designed closure direction deg	Actual drilled direction deg			$\Delta\phi$ deg	ratio $\frac{F_{\phi}}{F_f}$	Computed walking tendency	actual walking result
					ϕ_1	ϕ_2	$\Delta\phi/10\text{ m}$				
Unity 28#	714-778	Zerafa	220-240	270	283	270	-1.7	30-50	-(0.5-0.76)	-	-
	802-968	Adoke	220-240	270	272	265	0.422	30-50	-(0.5-0.76)	-	-
	968-1356	Aradeiba	220-250	270	265	265	0	20-50	-(0.34-0.76)	-	-
Unity 29#	1449-1589	Zarqa	200-210	200	204	205	0.071	0-(-10)	0-0.17	-	-
	1589-2011	Aradeiba	200-210	200	205	207	0.048	0-(-10)	0-0.17	-	-
	2011-2219	Bentiu	200-210	200	207	223	0.77	0-(-10)	0-0.17	-	-
Unity 30#	613-751	Zarafa	220	92	107	95	-0.22	-128	0.79	-	-
	882-1215	Adoke	220	92	95	107	0.361	-128	0.79	-	-
	1390-1919	Aradeiba	220	92	89	93	0.076	-128	0.79	-	-
	2081-2379	Bentiu	220	92	93	95	0.124	-128	0.79	-	-

Table 2: Surveying data and theoretical analysis (for Inclined well Unity 30#)

Depth	Inclination	azimuth	$\phi\psi$ deg	F_x N	F_y N	Computed building	Actual building	Computed walking	Actual walking
365.4	2.167	50	40	385.2	-323.2			-	-
385	3.834	36	30	415.2	-239.7			-	-
405	5.8264	18	10	434.3	-76.6			-	-
415	6.44	11	2	433.7	-15.2			-	-
436	9.2	9	0	388.3	0				-

The following data were taken from the holding section of the well Unity 30# at the Unity oil field-Sudan:

depth L: 1150 ~ 1270 m;

average inclination $\alpha=12^\circ$;

weight on bit $P_B = 21$ metric tons = 198355 N;

HBA: $\phi 244$ tri-cone bit (95/8" HP₂) + bit sub (630×520) + stabilizer S_1 ($\phi 243$ mm) + short collar 7" ($\phi 178$ mm×3) + stabilizer S_2 ($\phi 243$ mm) + non-magnetic collar 7" ($4\phi 177.8$ mm × 9 m) + stabilizer S_3 ($\phi 243$ mm) + collar 7" ($\phi 177.8$ mm × 9 m) + stabilizer S_4 ($\phi 243$ mm) + collar 7" ($\phi 177.8$ mm×27 m) + connector sub (521 × 410) + stabilizer S_5 ($\phi 241$ mm) + drill pipe 5" ($\phi 127$ mm).

The result isotropic index $H=0.02613$.

RESULTS

The natural formation force F_f has a tendency to make the hole axis approaches the normal line of the bedding planes. So the inclination will increase for larger weight on bit. Besides, larger dip will cause serious hole deviation problem in straight drilling. In the same time, as the anisotropy of actual bit exists, the drilling direction is different from that of resultant force on bit even in isotropic formation.

The data recorded in Table 1 were taken from three neighboring wells in the Unity oil field-Sudan. It is seen that the computed walking tendency are coincident with actual field results except some minor diversities.

The data recorded in Table 2 were taken from well Unity 30#. In this well, the formation dip $\beta = 30^\circ$, the dip direction ($P_B=4$ tones (39200 N)). H is taken as $H=0.03$. It is apparent the computed predictions are basically coincident with the actual results.

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