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# Evaluation of Parameters Affecting Lifting Capacity in Directional Wells for Garraf Oil Field

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**Abstract**
The cutting transport problem in the drilling operation is very complex because many parameters impact the process, which is nonlinearity interconnected. It is an important factor affecting time, cost and quality of the deviated and horizontal well. The main objective is to evaluate the influence of main drilling Parameters, rheological properties and cuttings that characterise lifting capacity through calculating the minimum flow rate required and cutting bed height and investigate these factors and how they influenced stuck pipe problems in deviated wells for Garraf oil field. The results obtained from simulations using Well Plan™ Software were showed that increasing viscosity depends on other conditions for an increase or decrease fluid flow rate required, increasing cutting density, cutting size, and ROP requires an increased fluid flow rate and when increasing RPM, increasing mud weight reduces the fluid flow rate required hence better hole cleaning. The major findings from the analysis parameter that wellbore inclination, mud density and pipe rotation affect the minimum flow rate needed for good hole cleaning. The drilling section of a well with fluid rates below the minimum flow rate required is considered the major cause of mechanical stuck pipes. In sliding drilling mode, the flow must be increased above the critical flow rate to reduce the likelihood of mechanical stuck pipe. Also, cuttings properties, fluid rheology, and rate of penetration have some influence on cuttings transport.

**Keywords:** Minimum flow rate, cutting bed height, cutting transport, Garraf oil field

# تقييم العوامل المؤثرة على قابلية الرفع في الآبار الاتجاهية لحقل الغراف النفطي

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**الخلاصة**
تعتبر مشكلة نقل القطع الصخرية المحفورة في عملية الحفر معقدة للغاية لأن العديد من العوامل تؤثر على العملية وهذه العوامل لا ترتبط بعلاقة خطية واضحة و هي أحد العوامل المهمة التي تؤثر على الوقت والتكلفة والجودة للبئر الاتجاهي والأفقي. الهدف الرئيسي في هذه الدراسة لتقييم تأثير متغيرات الحفر والمواصفات الريولوجية ومواصفات القطع الصخرية المحفورة على قابلية الرفع من خلال حساب المعدل الأدنى للجريان المطلوب وحدث ارتفاع الطبقة االمتولدة على جدار البئر و ايضا تقييم هذه العوامل ومدى تأثيرها على مشكلة

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استعصاء الانابيب للابار المائلة في حقل الغراف النفطي. أظهرت النتائج باستخدام برنامج Well Plan ™ أن زيادة اللزوجة تعتمد على ظروف أخرى بالنسبة لزيادة أو تقليل معدل الجريان المطلوب ، زيادة كثافة وحجم القطع المحفورة و معدل الاختراق يتطلب زيادة معدل تدفق السوائل. زيادة دوران الانابيب ، زيادة كثافة سائل الحفريقلل من معدل الجريان المطلوب وبالتالي تنظيف البئر بشكل أفضل. االاستنتاجات الرئيسية بينت أن زاوية ميلان البئر ، وكثافة الطين ، ودوران الأنابيب تؤثر بشكل كبير على معدل الجريان الأدنى المطلوب لتنظيف البئر بشكل جيد. يجب .زيادة معدل االجريان فوق معدل الجريان الحرج اثناء عملية بناء الزاوية للبئر لتقليل احتمالية استعصاء الانابيب الميكانيكي. ايضا خصائص االقطع المحفورة ، وريولوجيا السوائل ، ومعدل الاختراق اظهرت تاثير على نقل القطع المحفورة.

## 1. Introduction

Hole cleaning and cuttings transportation are major considerations in the design of drilling operations. If the velocity of the fluid is not kept above a critical rate, many problems which may cause, such as stuck pipe, higher drag and force, difficulties in casing/cementing job in a logging operation and slow rate of penetration (ROP), especially in deviated and horizontal wells. Sifferman and Becker studied several parameters of drilling that affect cutting transport in inclined wells. These drilling parameters are following:
Annular mud velocity, Mud density, Mud rheology, Mud type (oil- or water-based), Cuttings size, rate of penetration (ROP), Drill pipe rotary speed, Drill pipe eccentricity, Drill pipe diameter and Hole angle[1].
Figure 1 summarises the main parameters affecting cutting transport with the degree of control in the field. Drill pipe eccentricity, hole size and inclination, drilling fluid density, cuttings size, drilling rate, drill pipe rotation, drilling fluid rheology, and flow rateaffectg cuttings transport with varying degrees [2].

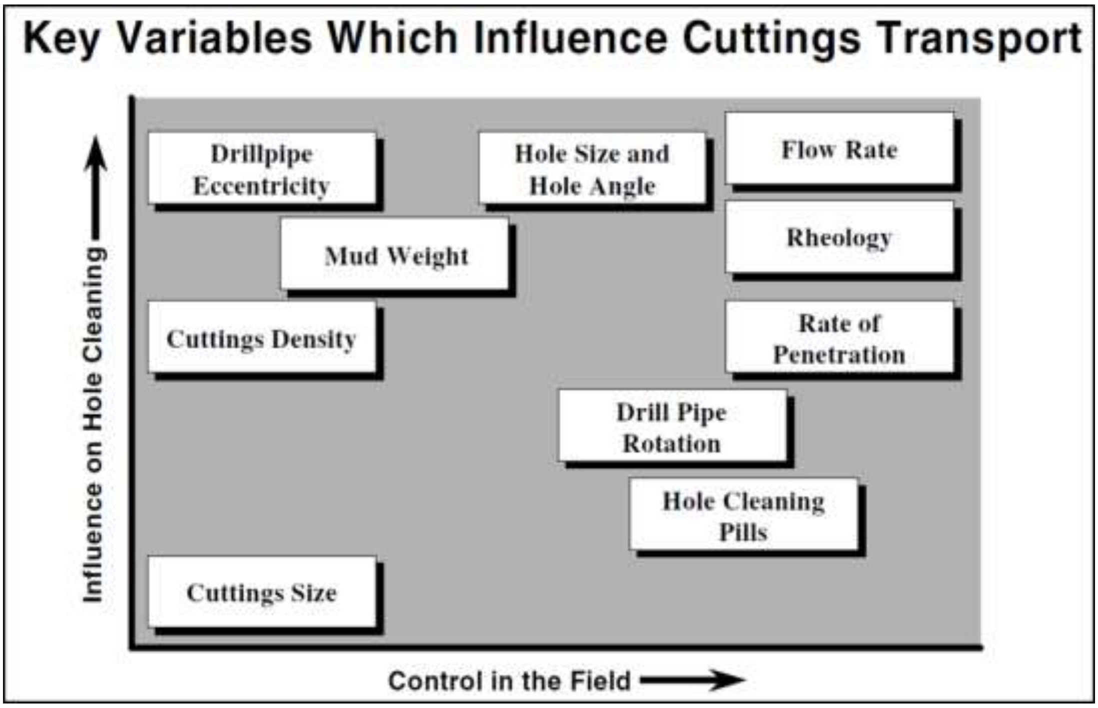



**Figure 1-** key parameters controlling cutting transport[3]

Martins et al. presented a set of enormous experimental programs that focused on examining the disintegration of a cuttings bed on the lower side of the wall of a horizontal wellbore section. The results indicated that the mud yield point was affected only in the bed abrasion of eccentric annulus[4]. Larsen et al. presented a new model for cuttings transport in high inclination wellbores to assist a drilling engineer in choosing the proper hydraulic parameters.

The experiment was focused on the annular fluid velocity required to prevent drilled cuttings from collecting in a hole. The purpose of the developed model was to predict the minimum fluid velocity required to keep all solid drilled cuttings moving award to surface without accumulation [5]. zbayoglu et al. developed a computer program for a coiled tubing transport efficiency model in an inclined wellbore. This study finds that flow rate and fluid viscosity are major parameters affected by wellbore cleaning. Turbulent flow is better for reducing bed development [6]. Duan et al. investigated the affected cutting size on cutting transport in in the clined wellbore. This study showed that cuttings size had significant differences in cuttings transport. Smaller cuttings produced a higher accumulation or concentration than large cuttings in a horizontal wellbore when the experiment used water as drilling mud [7]. Yu et al. investigated the parameters that affect hole cleaning in horizontal and inclined well. They concluded that drill pipe revolution, temperature degree and rheological properties of the drilling mud significantly influence hole cleaning efficiency[8]. Menegbo et al. presented a mathematical cutting transport model in the annulus wellbore that depended on the non-Newtonian viscosity model's power law. The results showed that the annular velocity and the rheological properties of the fluid are the main factors controlling and affecting cutting transport in the wellbore. Cutting size and drilling fluid density influenced the cuttings transport ratio[9].

In this study, an empirical cutting transport model (hole cleaning model of Well Plan™ Software) was used to predict the minimum flow rate and evaluate lifting capacity in deviated wells through analysis of variable influence in cutting transport and study stuck pipes problems happened in the field due to bad hole cleaning during operation, especially during slide mode drilling.

## 2. Area of study

The Garraf Oil Field lies in Iraq-Dhi Qar Governorate, about 85 km to the north of Nasiriyah city and 265 km southeastern Baghdad (Figure 2). The Garraf field is a SE-NW trending anticline 5 km wide and 24 km long. Many wells were drilled in the Garraf oil field since 1984 [10]. The Garraf oil field is currently produced from the Mishrif Formation, which is divided into upper, middle and lower parts. The middle and lower parts are reservoir units[11].

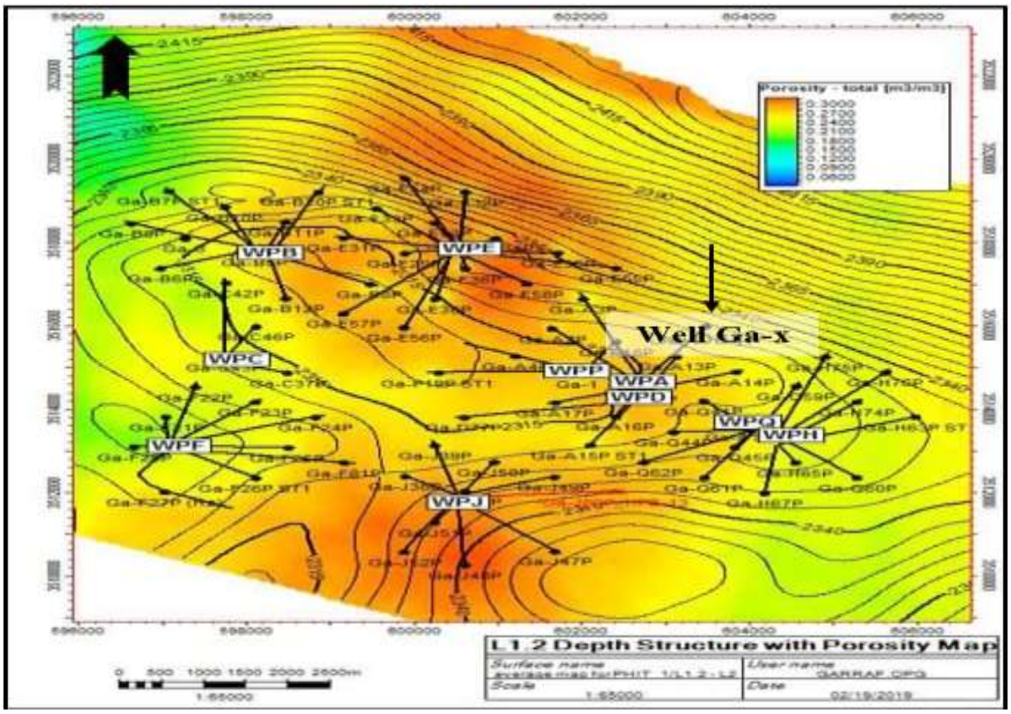



**Figure 2-** Depth structure map of the Garraf oil field with well Ga-x1 Location[12]

## 3. Materials and Methods

### 3.1 Hole Cleaning Model of Well Plan™ Software

Well Plan™ Software is alandmark program of Halliburton company used to analyse the drilling variables (flow rate, drilling mud density, drilling mud viscosity, rotation of drill pipe, wellbore angle, rate of penetration, and drilled cutting characterise), and to study the impact of these parameters on critical flow rate as a function of well inclination. This model is based on a mathematical equation that predicts the critical flow rate in an annular hole (flow rates required to remove drilled cuttings to transport to the surface and prevent an accumulation of cuttings beds during directional drilling. This is based on analysing forces acting on the cuttings and their associated dimensional groups. The model can be used to predict the critical (minimum) flow rate required to remove or prevent the formation of stationary cuttings [13].

Using this model, the important drilling variables effect on drilled cuttings transport have been evaluated. The parameters considered in this study for cutting transport analysis are include:

- Well inclination
- Cuttings density
- Cuttings load (ROP)
- Cuttings size
- Drill pipe rotation rate
- Mud density
- Mud rheology
- Mud velocity (flow rate)

Calculations were developed to describe the inter-relationship of these variables and the coefficients in the equations derived from the extensive experimental program[13].

### 3.2 Theory

This model is based on a mathematical model and developed to include most of the variables that affect cuttings transport. The coefficients in the equations are derived from the extensive experimental program and the following equations are used in the model [13]. These equations of this model are based on many references [8], [14-17].

**1. $n, K, \tau_o$ and Reynold's Number**

$$n = \frac{(3.32)(\log 10)\left(\tau_o + 2\mu_p\right)}{\left(\tau_o + \mu_p\right)} \tag{1}$$

$$K = \frac{\left(\mu_p + \tau_o\right)}{511} \tag{2}$$

$$\tau_o = (5.11K)^n \tag{3}$$

$$R_a = \frac{\rho v_{\mathrm{aa}}(2-n)(d_h - d_{\mathrm{bo}})^n}{\left(\frac{2}{3}\right) G_{\mathrm{pl}} K} \tag{4}$$

where:

$n$ = flow behavior index

$\tau_o$ = Mud yield point, Ib/100ft2

$\mu_p$ = Plastic viscosity, (c.p)

$K$ = Consistency factor

$R_a$= Reynolds number

$\rho$ = Fluid density, (ppg)

$v_{\mathrm{aa}}$= Average fluid velocity for annulus, (ft/s)

$d_h$ = Annulus diameter, (in)

$d_{\mathrm{bo}}$ = Pipe outside diameter, (in)

$G_{\mathrm{pl}}$= Power law geometry facto

**2. Concentrations Based on Rate of Penetration (ROP) in Flow Channel**

$$C_o = \frac{\left(\frac{Rd_b^2}{1471}\right)}{\left(\frac{Rd_b^2}{1471}\right)+Q_m} \qquad (5)$$

where:
$C_o$ = Cuttings feed concentration
R = Rate of penetration (ROP)
$d_b$ = bit diameter, (in)
$Q_m$ = Volumetric mud flow rate (GPM)

**3. Fluid Velocity Based on Open Flow Channel**

$$v_{\mathrm{aa}} = \frac{24.5Q_m}{d_h^2 - d_{\mathrm{bo}}^2} \qquad (6)$$

where:
$v_{\mathrm{aa}}$ = Average fluid velocity for annulus, (ft/s)
$Q_m$ = Volumetric mud flow rate
$d_h$ = Annulus diameter, (in)
$d_{\mathrm{bo}}$ = pipe outside diameter, (in)

**4. Coefficient of Drag around Sphere**

if $R_e < 225$

$$C_d = \frac{22}{\sqrt{R_a}} \qquad (7)$$

else, $C_d = 1.5$ (8)

where:
$R_e$ = Particle Reynolds number
$C_d$ = Drag coefficient

**5. Mud Carrying Capacity**

$$C_m = \frac{4g_c\left(\frac{d_c}{12}\right)(\rho_c - \rho)}{3\rho C_d} \qquad (9)$$

where:
$C_m$ = Mud carrying capacity
$g_c$ = Gravitational constant
$C_d$ = Drag coefficient

**6. Slip velocity**

if $v_{\mathrm{aa}} < 53.0$ $\quad v_s = (0.00516)v_{\mathrm{aa}} + 3.0006$ (10)
else, $v_{\mathrm{aa}} \geq 53.0$ $\quad v_s = (0.02554)(v_{\mathrm{aa}} - 53.0) + 3.28$ (11)
where:
$v_s$ = Slip velocity, (ft/s)
$v_{\mathrm{aa}}$ = Average fluid velocity for annulus, (ft/s)

**7. Settling Velocity in the Plug in a Mud with a Yield Stress**

$$U_{\mathrm{sv}} = \left[\left(\frac{4}{3}\right)\left(\frac{g_c\left(d_c^{1+bn}\right)(\rho_c - \rho)}{aK\rho_c^{1-b}}\right)\right]^{\frac{1}{2-b(2-n)}} \qquad (12)$$

where: $a = 42.9 - 23.9n, \quad b = 1 - 0.33n$
$U_{\mathrm{sv}}$ = Settling velocity, (ft/s)

**8. Angle of Inclination Correction Factor**

$$C_a = (\sin(1.33\alpha))^{1.33}\left(\frac{5}{d_h}\right)^{0.66} \qquad (13)$$

$$C_s = 1.286 - 1.04d_c \qquad (14)$$

where:
$C_a$ = angle of the inclination correction factor,
$\alpha$ = Wellbore angle, (deg)

$d_h$= Annulus diameter, (in)
$C_s$ = Cuttings size correction factor equation,

**9. Mud Weight Correction Factor**

if $(\rho < 7.7)$

$$C_m = 1.0 \quad (15)$$

else $$C_m = 1.0 - 0.0333(\rho - 7.7 \quad (16)$$

$C_m$ = Mud carrying capacity
$\rho$ = Fluid density, (ppg)

**10. Critical Wall Shear Stress**

$$\tau_{cw} = \left[a g_c \sin\alpha(\rho_c - \rho) d_c^{1+b} \rho^{b/2}\right]^{\frac{2n}{2n-2b+bn}} \quad (17)$$

where: $a = 1.732$
$b = -0.744$

$\tau_{\mathrm{cw}}$ =Critical wall shear stress, (psi)

**11. Critical Pressure Gradient**

$$p_{\mathrm{gc}} = \frac{2\tau_{\mathrm{cw}}}{r_c\left[1-\left(\frac{r_0}{r_c}\right)^2\right]} \quad (18)$$

where:
$p_{\mathrm{gc}}$ = Critical frictional pressure gradient, (psi/in)
$r_c$ = Radius of wellbore or casing, (in)
$r_o$ = Radius where shear stress is zero, (in)

**12. Total Cross-Sectional Area of the Annulus without Cuttings Bed**

$$A_c = \left(\frac{\pi}{4}\right)\left(\frac{d_h^2 - d_{\mathrm{bo}}^2}{144}\right) \quad (19)$$

where:
$A_c$ = Cross-sectional area of annulus. $(ft^2)$
$d_h$ = Annulus diameter, (in)
$d_{\mathrm{bo}}$ = pipe outside diameter, (in)

**13. Dimensionless Flow Rate**

$$\prod g_b = \prod\left[8 \times \frac{\frac{n}{2(1+2n)}}{(a)^{\frac{1}{b}}}\right]^{\frac{1}{2-(2-n)^b}} \times \left(1 - \left(\frac{r_p}{r_c}\right)^2\right)\left(1 - \left(\frac{r_p}{r_c}\right)^{\frac{6}{2-(2-n)^b}}\right) \quad (20)$$

where: $a = 16$ , $b = 1$

$\prod g_b$ = Dimensionless flow rate,
$r_p$ = Radius of drill pipe, (in)
$r_c$ = Radius of wellbore or casing, (in)

**14. Critical Flow Rate (CFR)**

$$Q_{\mathrm{cb}} = r_c^2\left[\frac{\rho g_c b^{\frac{1}{b}} r_c^{\left(\frac{1}{b+n}\right)}}{K\rho^{\left(\frac{1}{b-1}\right)}}\right]^{\frac{6}{2-b(2-n)}} \prod g_b \quad (21)$$

where:
$Q_{\mathrm{cb}}$ = Critical flow rate for bed to develop (GPM)

**15. Correction Factor for Cuttings Concentration**

$$C_{\mathrm{bed}} = 0.97 - \left(0.00231\mu_{\mathrm{pa}}\right) \quad (22)$$

where:
$C_{\mathrm{bed}}$ = Correction factor for cuttings concentration,
$\mu_{\mathrm{pa}}$ = Apparent viscosity, (c.p)

**16. Cuttings Concentration for a Stationary Bed by Volume**

$$C_{\text{bconc}} = C_{\text{bed}}\left(1.0 - \frac{Q_m}{Q_{\text{cb}}}\right)(1.0 - \emptyset_b)(100) \tag{23}$$

where:

$C_{\text{bconc}}$ = Cuttings concentration for a stationary bed by volume

$C_{\text{bed}}$ = Correction factor for cuttings concentration,

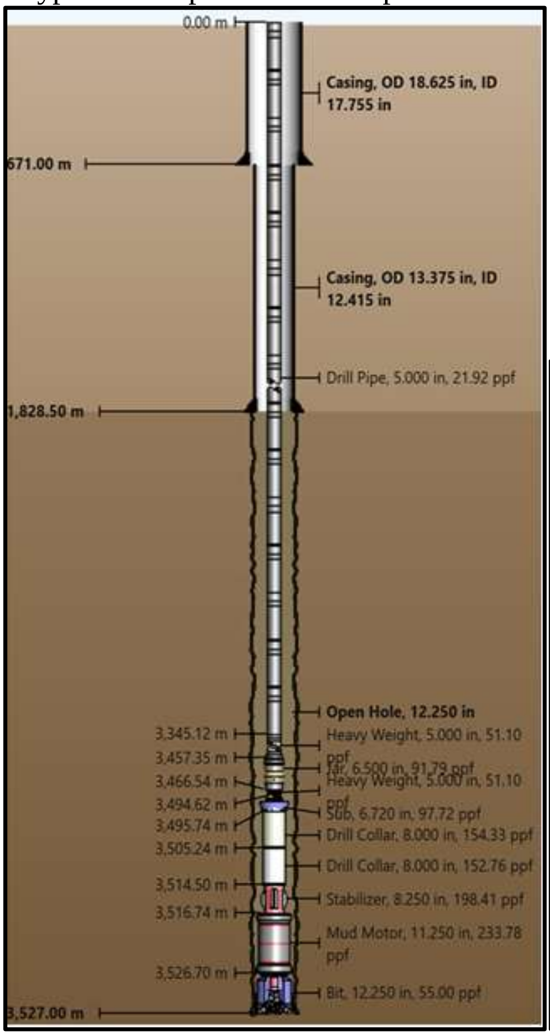
$Q_m$ = Volumetric mud flow rate (GPM)

$Q_{\text{cb}}$= Critical flow rate for the bed to develop (GPM)

$\emptyset_b$ = Bed porosity (dimensionless)

**3.3 Well geometry and string**

The well construction is given in Figure 3 and the string used in drilling the section 12.25-in is shown in Figure 4 below. Figure 3 represents the survey for well Ga-x with a maximum inclination of 64.91° in medium section 17.5in and a full tilt of 61.65° in last section 12.25, the type of well profile is S-shape.



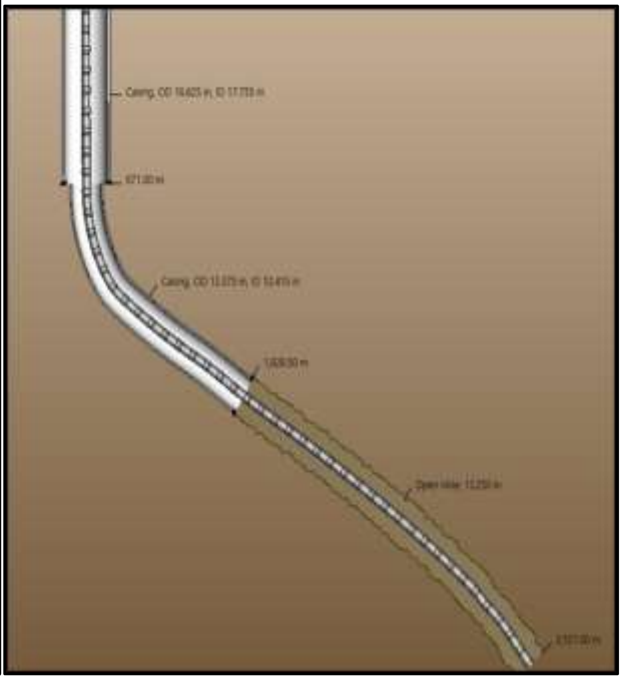



**Figure 3-** Deviated schematic of well Ga-x **Figure 4-** Drill string of well Ga-x

## 4. Results and Discussion

**4.1 Case Study1: Well Ga-x Deviated well**

In this study, critical fluid velocity for the last section of the well was calculated to range of inclination and compared the model results with the actual operation flow rate. All Input data are gathered from the final and daily drilling reports of well Ga-x as listed in Table 1.

**Table 1-** Field Drilling parameter data of Well Ga-x[12]

| **Well Type** | **Deviated well** |
|---|---|
| **Total depth (m)** | 3527 |
| **Wellbore size (in)** | 12.25 |
| **Drill pipe size (in)** | 5 |
| **Maximum Section inclination** | 61.65° |
| **Drilling fluid type** | WBM (Lime Polymer) |
| **MW (ppg)** | 10.4 – 10.8 |
| **YP (lb/100ft2)** | 13 - 20 |
| **PV (cp)** | 20 - 30 |
| **ROP (m/hr)** | 3 – 10 |
| **RPM/surface** | 50 -100 |

In well Ga-x, a mechanical stuck pipe at depth 2691m and many tight holes accrued during tripping. We investigated the causes of these problems by studying hole cleaning by determining the minimum flow rate required and cutting bed height. Table 2 shows the minimum flow rate calculated using the hole cleaning model for deviated well in section 12.25-in. The results showed that the minimum flow rate required to prevent growing the cutting bed in the wellbore was more compared with the actual flow rate used in drilling. A good hole cleaning occurs when the actual flow rate exceeds the minimum flow rate. At depth 2221m and depth (2369m) with an angle of about 61°, tight spots happened, and at these two points, the actual flow rate used (802GPM) was less than the minimum flow rate required (833 and 831 GPM). At depth 2691m, during sliding mode drilling of the Hartha Formation (limestone), stuck pipe happened, and the minimum flow rate required is 970GPM, while the actual flow rate used was less (750GPM) and cutting bed formed 2.1in at this depth. So, this considers a major cause of mechanical stuck pipe which happened. Figure 5 shows the actual rate used in drilling with the minimum flow rate determined by this model. From Figure 5, it was noticed that the difference between the actual flow rate and the minimum flow rate required to lead to hole problems such as stuck pipe, which accrued at depth2691m.

**Table 2-** Actual flow rate and minimum flow rate calculated by Well Plan software model of well Ga-x

| MD (m) | Angle | ROP m/hr | RPM | Fluid density (ppg) | YP (lb/100$ft^2$) | PV (cp) | Cutting density gm/cc | Cutting size (in) | Actual flow rate (GPM) | Min flow rate (GPM) Well Plan Model | Cutting Bed Height (in) | Notice |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1993 | 59.59 | 5 | 50 | 10.4 | 15 | 27 | 2.6 | 0.07 | 800 | 835 | - | - |
| 2221 | 60.99 | 7 | 60 | 10.4 | 16 | 28 | 2.6 | 0.07 | 802 | 833.5 | 0.33 | Tight spots |
| 2369 | 60.81 | 7 | 60 | 10.4 | 16 | 29 | 2.6 | 0.07 | 802 | 831 | 0.29 | Tight spots |
| 2670 | 60 | 6 | 75 | 10.6 | 19 | 30 | 2.6 | 0.07 | 810 | 758 | 0 | No grow bed |
| 2691 | 60.21 | 3 | 0 | 10.6 | 19 | 30 | 2.6 | 0.07 | 750 | 970 | 2.1 | Sliding- stuck pipe happen |
| 3226 | 52.53 | 3.4 | 80 | 10.6 | 13 | 27 | 2.6 | 0.07 | 780 | 666 | - | - |
| 3527 | 39.5 | 4.5 | 50 | 10.6 | 13 | 28 | 2.6 | 0.07 | 778 | 630 | - | - |

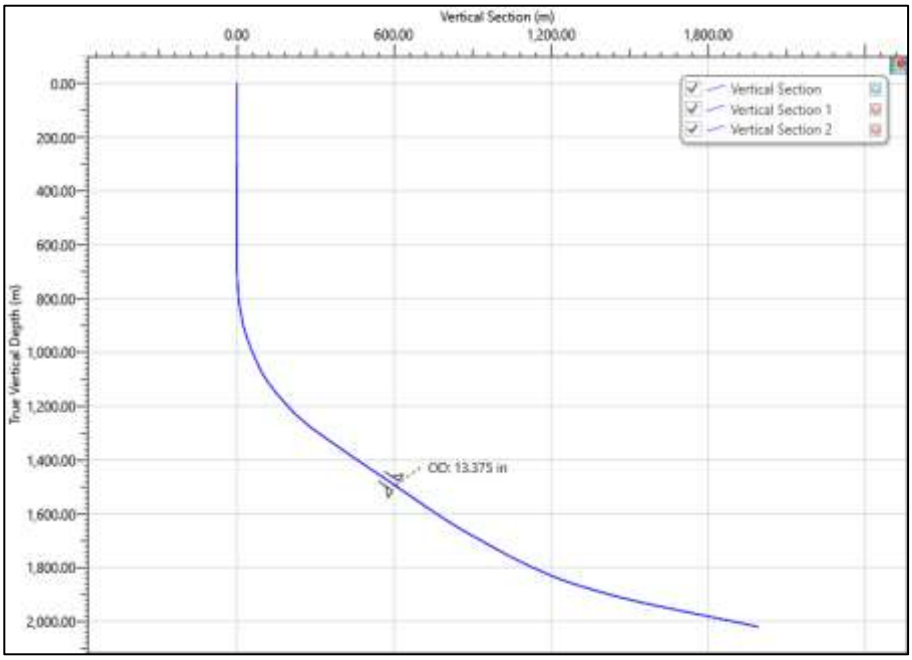



**Figure 5-** Actual flow rate and minimum flow rate required vs depth of well Ga-x

### 4.2 Case Study 2: Parametric sensitivity analysis

In this part of the paper, we investigated the effect of parameters on behavior of cutting transport through calculated minimum flow rate and cutting bed when the parameters varied. Well Plan™ Software was used to analyze the impact of drilling parameters on hole cleaning. The calculation was done to predict the bed height in the wellbore. Two points from the designed well were involved angle range from 0 to 80 degrees (Figure 6). They used to study the effect of each parameter, one point inside the casing (13.375in) at depth 1600m with angle 60° and another point inside the open hole (bit size12. 25in) at a depth of 2000 m with the same angle.

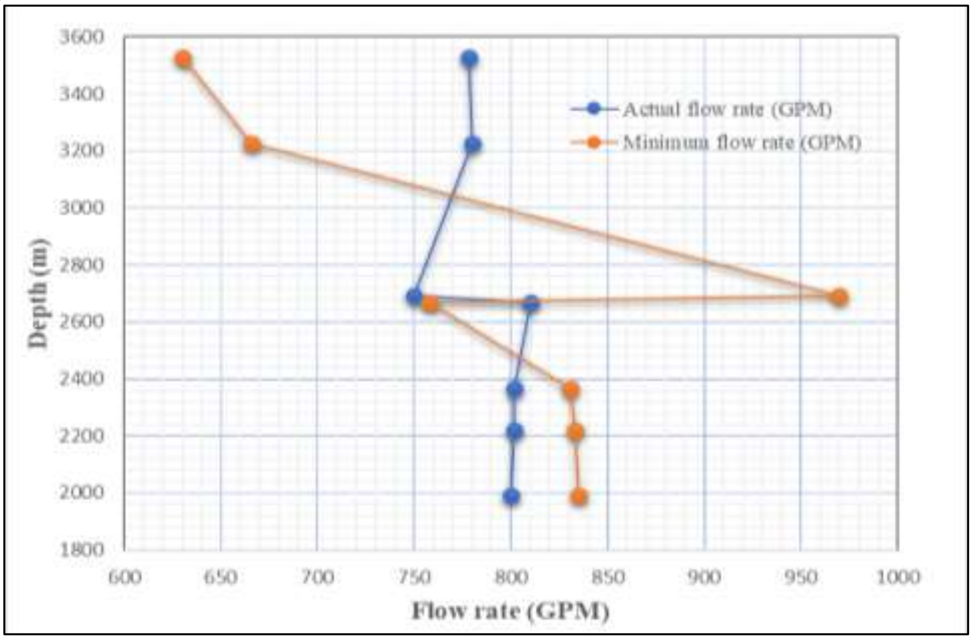



**Figure 6-** Vertical plane section of the designed well with inclination from 0° to 80°

### 4.2.1 Effect of well inclination

As seen in Figure 7, If the inclination is 25°, the flow rate requires about 538 GPM, then when angle begins to change and gradually increase to 50°, the minimum flow required increases to 813 GPM and at least needs 972 GPM when inclination 75°. The result generally shows that the hole-cleaning problem increases as the well inclination increases. In other words, a higher flow rate is required for a highly inclined well. The effect of azimuth, also simulated, shows that azimuth has no impact on hole-cleaning. As can be seen in Figure 7 minimum flow rate decreased at an inclination angle 80deg, and that happened because the hydraulic diameter is reduced (drill collar and mud motor against this angle; see Figure 4). The minimum flow rate decreased when the drill string diameter increased.

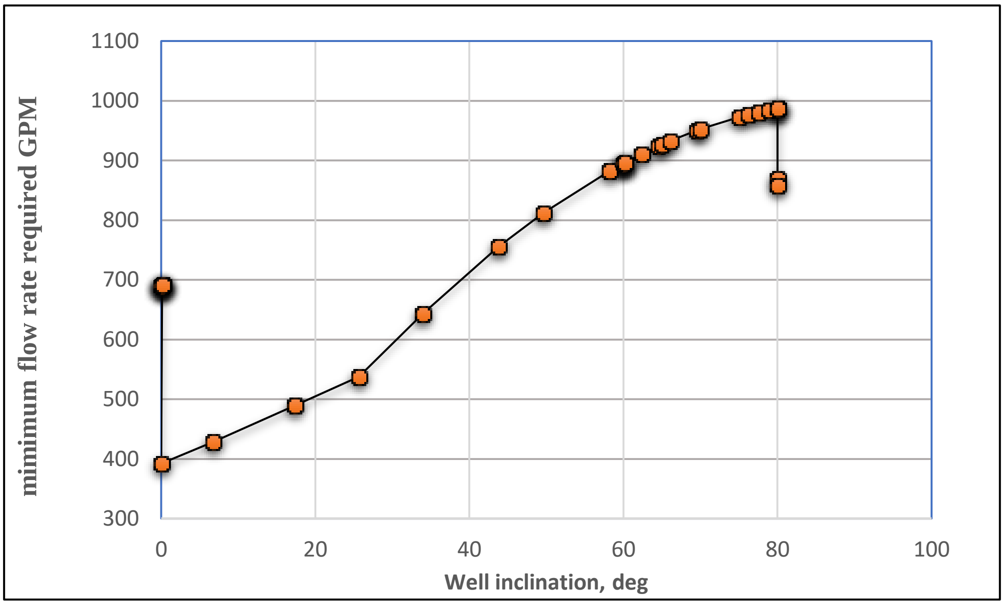



**Figure 7-** Minimum flow rate required vs well inclination of the designed well

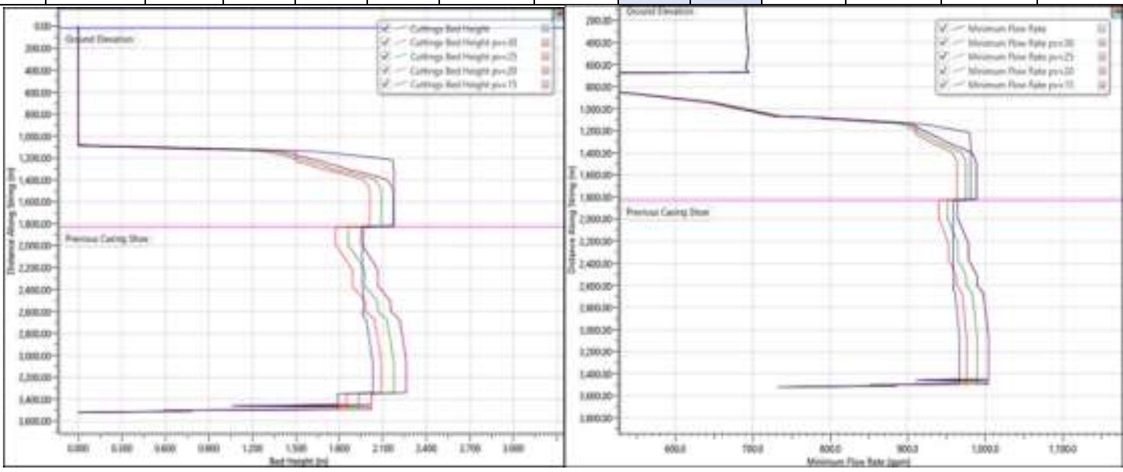
### 4.2.2 Effect mud rheology properties

For the considered mud rheological properties, plastic viscosity varied, but the other parameters were kept constant. The simulation results showed that, at point 1600m with angle 60° the lowest minimum flow rate required when PV=20 cp, at depth 2000m with angle 60° and hole size 12.25in, and also when PV=20 cp gave lowest minimum flow rate for cutting transport (Figure 8a). The inclination of 70° at a depth 2500m, the PV=15 cp gave the lowest minimum flow rate. The PV result same effect on cutting bed height. The curve with PV=15 gave large cutting bed inside casing 13.375in, and then cutting bed height decrease inside open hole 12.25in with same angle 60°; however the PV=20 cp gave less height of cutting bed in above (Figure 8b). At an angle increased to more than 70° the PV=15cp gave the low cutting bed height.

**Table 3-** Minimum flow rate and cutting bed height calculated as function of plastic viscosity

| MD (m) | Well bore size (in) | Drill pipe (in) | Angle | ROP (m/hr) | RPM | Fluid density (ppg) | YP (lb/100$ft^2$) | PV (cp) | YP/PV | Cutting density (gm/cc) | Cutting size (in) | Minimum flow rate (GPM) | Cutting Bed Height (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 15 | 30 | 0.5 | 2.6 | 0.07 | 990 | 2.15 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 15 | 30 | 0.5 | 2.6 | 0.07 | 964 | 1.94 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 15 | 25 | 0.6 | 2.6 | 0.07 | 975 | 2.08 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 15 | 25 | 0.6 | 2.6 | 0.07 | 951 | 1.857 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 15 | 20 | 0.75 | 2.6 | 0.07 | 964 | 2.0 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 15 | 20 | 0.75 | 2.6 | 0.07 | 940 | 1.75 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 15 | 15 | 1 | 2.6 | 0.07 | 980 | 2.18 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 15 | 15 | 1 | 2.6 | 0.07 | 959 | 1.97 |



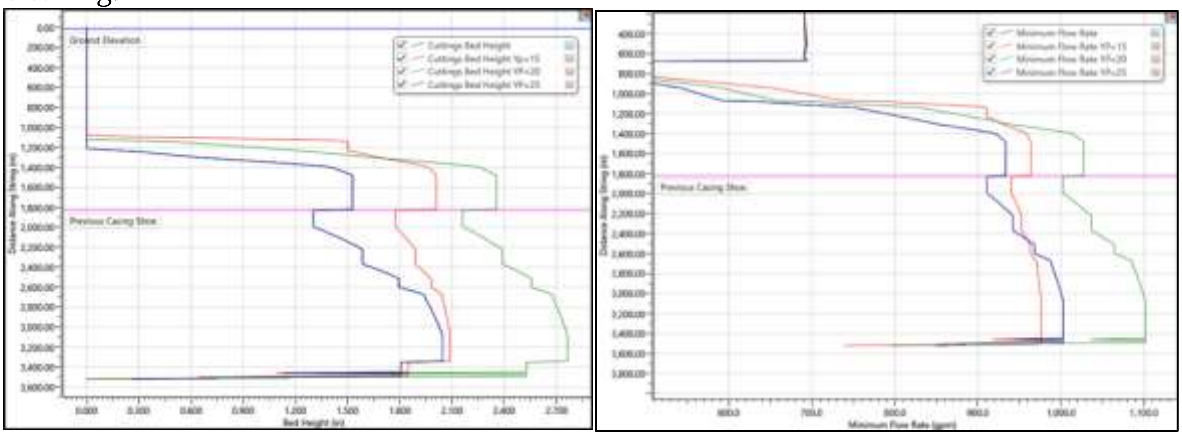
**(a)** **(b)**

**Figure 8-** Effect of Plastic viscosity (PV) on (a) minimum flow rate required (b) cutting bed height

Figures 9a&b show the yield point effect on minimum and flow rate and cutting bed height. The results show that when the angle below 70° and PV=20 cp remain constant, the YP=25 gave the lowest minimum flow rate required. When an angle increases to more than 70°, the lowest minimum flow rate appears when YP=15. The cutting bed height decreased when YP=25 for a long inclination well.

Higher yield values of mud and yield-point/plastic-viscosity (YP/PV) ratio provide better cuttings transport. The effect of yield point value is significant in the range of 0 to 45 ° hole inclination and becomes small or even negligible in the range of 55 to 90°. The effects of mud yield value and YP/PV ratio are more significant for lower annular fluid velocities [18].

As seen in the results of the YP/PV increase, the flow rate required to clean the cutting out of the hole showed decreases. For an angle more than 70°, YP/PV=0.75 ratio gave better hole cleaning.



**(a)** **(b)**

**Figure 9-** Effect of Yield point (YP) on (a) minimum flow rate required (b) cutting bed height bed height

**Table 4-** Minimum flow rate and cutting bed height calculated as a function of Yield Point varied

| MD (m) | Well bore size (in) | Drill pipe (in) | Angle | ROP (m/hr) | RPM | Fluid density (ppg) | YP (lb/100$ft^2$) | PV (cp) | YP/PV | Cutting density (gm/cc) | Cutting size (in) | Minimum flow rate (GPM) | Cutting Bed Height (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 15 | 20 | 0.75 | 2.6 | 0.07 | 964 | 2.0 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 15 | 20 | 0.75 | 2.6 | 0.07 | 940 | 1.75 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 20 | 20 | 1 | 2.6 | 0.07 | 1026 | 2.35 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 20 | 20 | 1 | 2.6 | 0.07 | 1000 | 2.15 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 25 | 20 | 1.25 | 2.6 | 0.07 | 933 | 1.5 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 25 | 20 | 1.25 | 2.6 | 0.07 | 910 | 1.3 |

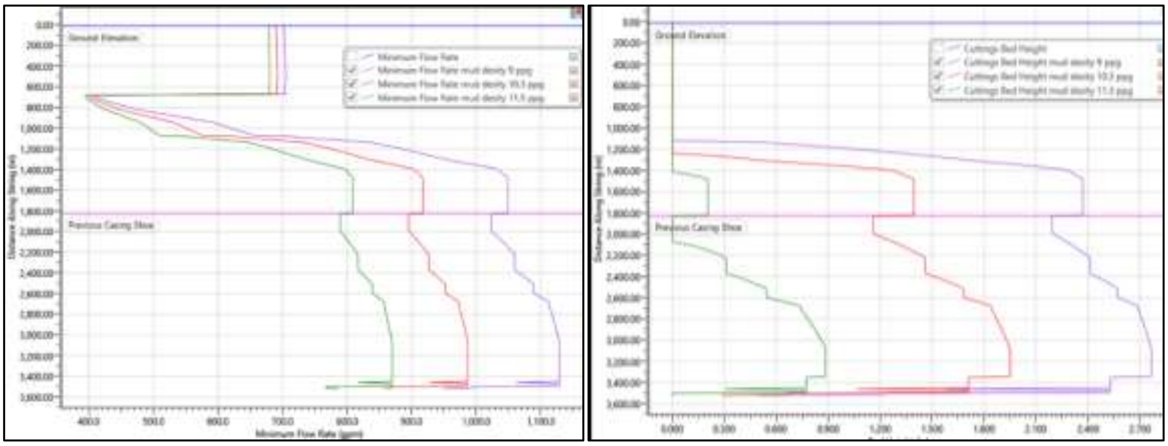
**Table 5-** Minimum flow rate and cutting bed height calculated as function of mud density varied

| MD (m) | Well bore size (in) | Drill pipe (in) | Angle | ROP (m/hr) | RPM | Fluid density (ppg) | YP (lb/100$ft^2$) | PV (cp) | Cutting density (gm/cc) | Cutting size (in) | Minimum flow rate (GPM) | Cutting Bed Height (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 9 | 25 | 17 | 2.6 | 0.07 | 1047 | 2.37 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 9 | 25 | 17 | 2.6 | 0.07 | 1023 | 2.19 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 917 | 1.39 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 895 | 1.16 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 11.5 | 25 | 17 | 2.6 | 0.07 | 808 | 0.2 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 11.5 | 25 | 17 | 2.6 | 0.07 | 790 | 0 |

### 4.2.3 Effect of mud density

Three drilling fluid densities were considered for the effect of fluid density on cutting transport phenomenon. These are 9, 10.3 and 11.5 ppg. The other parameters were kept constant, as shown in table 5. The simulation results show that as mud density increases, the minimum flow rate required to clean the hole decreases. Figure 10a shows the simulation result, and the mud weight significantly affects transport. The cutting bed height also decreased as mud density increased, as seen in Figure 10b).

Decreasing the size of cuttings beds height by increasing mud weight, annular velocity, and drill pipe rotation and, if possible, reducing hole angle. Mud density is the most important variable affecting cuttings-bed height [1].



**(a)** **(b)**

**Figure 10-** Effect of mud density on (a) minimum flow rate required (b) cutting bed height bed height

### 4.2.4 Effect of rotational speed (RPM)

The results showed that increased rotational speed of drill string leads to increased cleaning rate. At depth 2000m with RPM=90 minimum flow rate is equal to 850 GPM while in the same position, but RPM=0, the minimum velocity required is increased to 1111 GPM see Table 6 and Figure 11 (a) and (b). As in cutting bed height increased when low RPM or zeroes during sliding mode drilling and that may cause mechanical stuck and hence lost time and money. The rotational speed improves the flow on the bottom section of the annulus, increasing the drag force to perform the cleaning process and decreasing the volume of cuttings deposited on the low side of the wellbore. The cutting bed is formed symmetrically if the drill pipe does not rotate, the cutting bed becomes asymmetric increasing the rotation speed.

**Table 6-** Minimum flow rate and cutting bed height calculated as a function of rotational speed (RPM)

| MD (m) | Well bore size (in) | Drill pipe (in) | Angle | ROP (m/hr) | RPM | Fluid density (ppg) | YP (lb/100$ft^2$) | PV (cp) | Cutting density (gm/cc) | Cutting size (in) | Minimum flow rate (GPM) | Cutting Bed Height (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1600 | 13.375 | 5 | 60 | 7 | 0 | 10.3 | 25 | 17 | 2.6 | 0.07 | 1140 | 2.83 |
| 2000 | 12.25 | 5 | 60 | 7 | 0 | 10.3 | 25 | 17 | 2.6 | 0.07 | 1111 | 2.68 |
| 1600 | 13.375 | 5 | 60 | 7 | 30 | 10.3 | 25 | 17 | 2.6 | 0.07 | 981 | 1.92 |
| 2000 | 12.25 | 5 | 60 | 7 | 30 | 10.3 | 25 | 17 | 2.6 | 0.07 | 958 | 1.72 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 917 | 1.39 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 894 | 1.15 |
| 1600 | 13.375 | 5 | 60 | 7 | 90 | 10.3 | 25 | 17 | 2.6 | 0.07 | 871 | 0.92 |
| 2000 | 12.25 | 5 | 60 | 7 | 90 | 10.3 | 25 | 17 | 2.6 | 0.07 | 850 | 0.66 |

**(a)** **(b)**

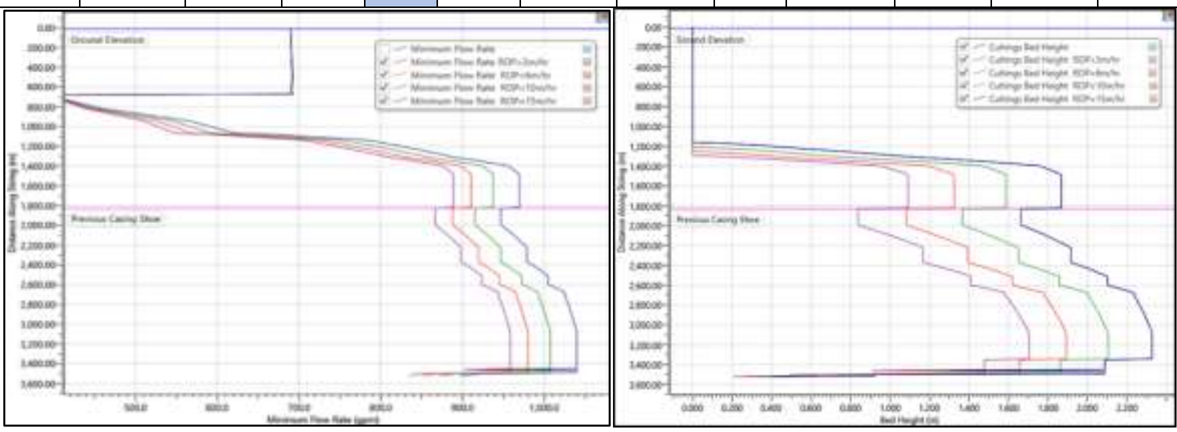
**Figure 11-** Effect of revolution per minute (RPM) on (a) minimum flow rate required (b) cutting bed height bed height

### 4.2.5 Effect of rate of penetration (ROP)

The increase in ROP leads to an increased minimum flow rate required for cutting transport in well bore and increased cutting bed height (Figure 12a). At a depth of1600 m, the minimum flow rate required about 890 GPM when ROP=3m/hr, but at the same depth, the flow rate required about 970 GPM when ROP=15m/hr see table 7. From the results in table 7- we notice a slightly increasing in minimum flow rate when increased ROP. Also, this is increasingly affected by the bit size (drilling hole size). So, the ROP has a moderate negative effect on cutting transport in a deviated well. An increase in ROP increases the hydraulic requirement for effective hole cleaning [19].

**Table 7-** Minimum flow rate and cutting bed height calculated as a function of the rate of penetration (ROP)

| MD (m) | Well bore size (in) | Drill pipe (in) | Angle | ROP (m/hr) | RPM | Fluid density (ppg) | YP (lb/100$ft^2$) | PV (cp) | Cutting density (gm/cc) | Cutting size (in) | Minimum flow rate (GPM) | Cutting Bed Height (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1600 | 13.375 | 5 | 60 | 3 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 890 | 1.08 |
| 2000 | 12.25 | 5 | 60 | 3 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 865 | 0.83 |
| 1600 | 13.375 | 5 | 60 | 6 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 910 | 1.31 |
| 2000 | 12.25 | 5 | 60 | 6 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 888 | 1.07 |
| 1600 | 13.375 | 5 | 60 | 10 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 937 | 1.58 |
| 2000 | 12.25 | 5 | 60 | 10 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 914 | 1.36 |
| 1600 | 13.375 | 5 | 60 | 15 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 970 | 1.86 |
| 2000 | 12.25 | 5 | 60 | 15 | 60 | 10.3 | 25 | 17 | 2.6 | 0.07 | 947 | 1.66 |

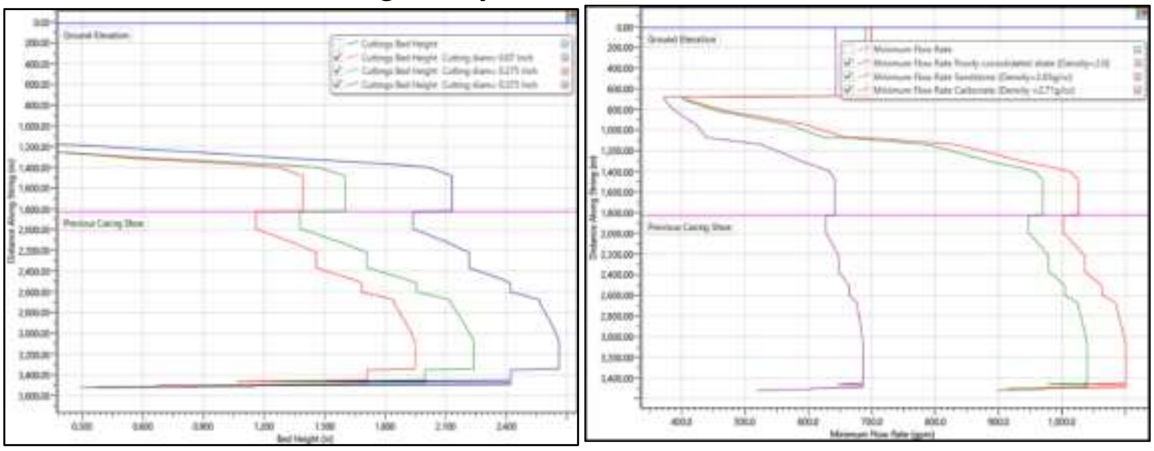


**(a)** **(b)**

**Figure 12-** Effect of Rate of penetration (ROP) on (a) minimum flow rate required (b) cutting bed height

### 4.2.6 *Effect of cutting density*

For this simulation, three types of cutting density were considered ( Table 8). The operational parameters and the cutting properties are kept constant throughout the simulation. The main objective was to study the sensitivity of cutting density minimum flow rate required. The cutting density is an uncontrol variable, but the amount of density affects the minimum flow rate required and the efficiency of hole cleaning. In Table 8, at a depth of 1600m and cutting density of 2.71 gm/cc (Carbonate rock), the minimum flow rate required about 1025 GPM, but when the cutting density is 2 gm/cc (Poorly consolidated shale), the minimum flow rate required to drop to 643 GPM. The influence of cutting density on minimum flow rate is slightly more significant, as shown in Figure 13 (a) that it is a large-scale difference between curve 2 gm/cc and curve 2.71gm/cc. That is the same effect on the cutting bed height (Figure 13 b). The cutting bed formed as the cutting density increased. Hole angle and well bore size had the same effect when cutting density varied.



(a) (b)

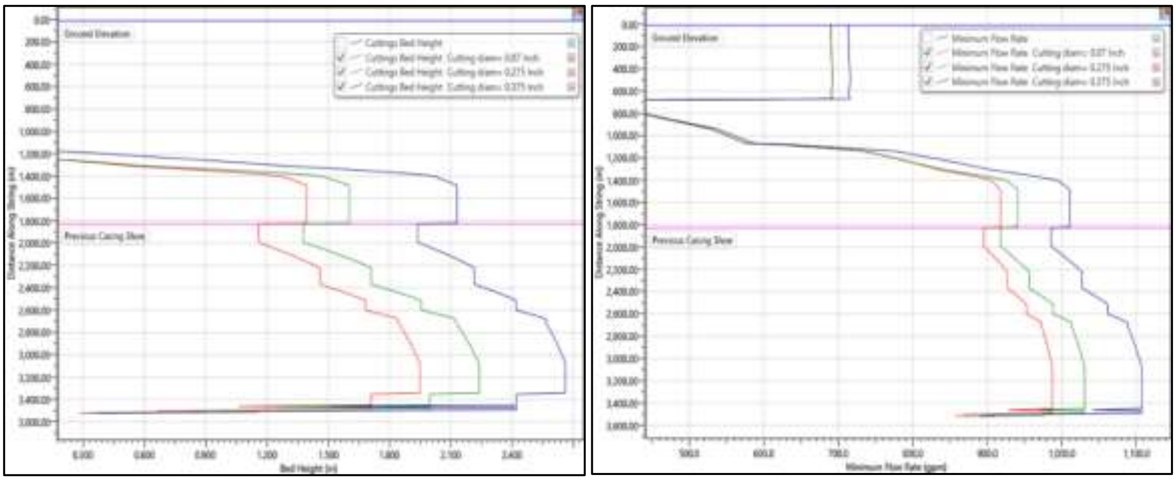
**Figure 13-** Effect cutting density on (a) minimum flow rate required (b) cutting bed height

**Table 8-** Minimum flow rate and cutting bed height calculated as a function of cutting density varied

| MD (m) | Well bore size (in) | Drill pipe (in) | Angle | ROP (m/hr) | RPM | Fluid density (ppg) | YP (lb/100$ft^2$) | PV (cp) | Cutting density (gm/cc) | Cutting size (in) | Minimum flow rate (GPM) | Cutting Bed Height (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.00 | 0.07 | 643 | 0 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.00 | 0.07 | 628 | 0 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.60 | 0.07 | 970 | 1.86 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.60 | 0.07 | 947 | 1.66 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.71 | 0.07 | 1025 | 2.26 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.71 | 0.07 | 1000 | 2.08 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.00 | 0.07 | 643 | 0 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.00 | 0.07 | 628 | 0 |

### 4.2.7 *Effect of cutting size*

Cutting size is one of the un-controller parameters affecting the hole cleaning. For this simulation, small, medium and large-sized cuttings were considered, and other parameters were kept. for the analysis. Table 9- shows the simulation result. The result shows that more flow rate is required to clean the hole for the larger cutting size. In general, larger and heavier cutting makes the hole cleaning more difficult and requires higher pump rates for high-viscosity fluids. As indicated in Figures 14a and b, the impact of cutting size on flow rate is not fundamental. The minimum flow rate required is the same behaviour for different sizes when the angle is proximally below 30°. Figure 20 shows the analysis of the effect of cutting size on cutting bed height. When the cutting size increased from 0.07 inches to 0.375 inches, the cutting bed increased from 1.16 inches to 1.93 inches.



**(a)** **(b)**

**Figure 14-** Effect cutting size on (a) minimum flow rate required; (b) cutting bed height

**Table 9-**Minimum flow rate and cutting bed height calculated as a function of cutting size varied

| MD (m) | Well bore size (in) | Drill pipe (in) | Angle | ROP (m/hr) | RPM | Fluid density (ppg) | YP (lb/100$ft^2$) | PV (cp) | Cutting density (gm/cc) | Cutting size (in) | Minimum flow rate (GPM) | Cutting Bed Height (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.60 | 0.07 | 1010 | 1.39 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.60 | 0.07 | 985 | 1.16 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.60 | 0.275 | 940 | 1.60 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.60 | 0.275 | 917 | 1.38 |
| 1600 | 13.375 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.60 | 0.375 | 916 | 2.13 |
| 2000 | 12.25 | 5 | 60 | 7 | 60 | 10.3 | 25 | 17 | 2.60 | 0.375 | 895 | 1.93 |

## 5. Conclusions

According to the analysis of the data of well Ga-x, the main conclusions of the present study are:

1- As much as the possible actual flow rate is greater than the minimum flow rate to decrease hole problems.

2- Drilling section of a well with fluid rates below the minimum flow rate required is considered the major cause of mechanical stuck pipes. And sliding drilling mode in directional well required more flow rate to reduce the mechanical stuck pipe problem.

3- The influences of borehole inclination angle, drilling fluid rheological parameters, drilling fluid density, pipe rotation, ROP, cutting density and cutting size on the minimum flow rate required for cutting transport were studied using Well Plan™ Software. These parameters showed significant effects on cuttings transport efficiency.

4- The simulation results are in trend with the results of the reviewed researcher.

- Increasing viscosity depends on other conditions for an increase or decrease the fluid flow rate
- Increasing cutting density, cutting size, and ROP requires an increased fluid flow rate
- Increasing RPM, and increasing mud weight reduce the fluid flow rate required.

5- Wellbore inclination, fluid density and pipe rotation significantly affect cutting transport and hole cleaning becomes harder as the angle increase.
6- The hole cleaning model of Well Plan™ Software shows close results with actual operation parameters.

**Nomenclature**

ROP =Rate of penetration
RPM = Revelation per minute
CTFV= Critical Transport Fluid Velocity
$A_c$ = Cross sectional area of annulus
$b_d$ = Bit diameter
$C_a$ = Angle of inclination correction factor
$C_{bed}$ = Correction factor for cuttings concentration
$C_{bconc}$ = Cuttings concentration for a stationary bed by volume
$C_d$ = Drag coefficient
$C_m$ = Mud carrying capacity
$C_o$ = Cuttings feed concentration
$C_s$ = Cuttings size correction factor equation
$d_{bo}$ = pipe outside diameter
$d_c$ = Cuttings diameter
$d_h$ = Annulus diameter
$G_{pl}$ = Power-law geometry factor
$g_c$= Gravitational constant
K = Consistency factor
n = Flow behavior index
$p_{gc}$ = Critical frictional pressure gradient
$Q_{cb}$ = Critical flow rate for a bed to develop
$Q_m$ = Volumetric mud flow rate
R = Rate of penetration (ROP)
$R_a$ = Reynolds number
$R_e$ =Particle Reynolds number
$r_c$ = Radius of wellbore or casing
$r_o$ = Radius where shear stress is zero
$r_p$ = Radius of drill pipe
$U_{SV}$ = Settling velocity
$v_{aa}$ = Average fluid velocity for annulus
$v_s$ = Slip velocity
$\alpha$ = wellbore angle
$\gamma$ = Shear rate
$\mu_p$ = Plastic viscosity
$\mu_{pa}$ = Apparent viscosity
$\Pi g_b$ = Dimensionless flow rate
$\rho$ = Fluid density
$\rho_c$ = Cutting density
$\tau$ = Shear stress
$\tau_{cw}$ = Critical wall shear stress
$\tau_o$ = Mud yield point
$\emptyset_b$ = Bed porosity

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