Estimation of Lifting Capacity for Selected Wells in Rumaila Field

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ABSTRACT

This paper deals with studying the effect of hole inclination angle on computing slip velocity and consequently its effect on lifting capacity. The study concentrates on selected vertical wells in Rumaila field, Southern Iraq. Different methods were used to calculate lifting capacity. Lifting capacity is the most important factor for successful drilling and which reflex on preventing hole problems and reduces drilling costs. Many factors affect computing lifting capacity, so hence the effect of hole inclination angle on lifting capacity will be shown in this study. A statistical approach was used to study the lifting capacity values which deal with the effect of hole inclination angle and those values that do not put the effect of hole inclination angle under consideration. Results illustrated that low hole inclination angles had a slight effect on lifting capacity values , but this study could be used on high inclination angles like directional wells or horizontal wells , hence high hole inclinations angle will yields high effect on lifting capacity values.

Key words: hole cleaning; cuttings transport; lifting capacity; hole inclination angle; slip velocity.

تخمين قابلية الرفع لابار مختارة في حقل الرميلة

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الخلاصة

هذا البحث يتناول دراسة تاثير زاوية انحراف البئر على حساب سرعة الانزلاق و بالتالي على قابلية رفع الصخور.
الدراسة تركّزت على ابار عمودية مختارة في حقل الرميلة جنوبي العراق.
طرق مختلفة تم استخدامها لحساب قابلية رفع الصخور . قابلية رفع الصخور هي العامل الاكثر أهمية لعملية حفر ناجحة و التي تنعكس على تجنب مشاكل الحفر و تخّفض كلفة الحفر. عوامل كثيرة تؤثر على حساب قابلية رفع الصخور ، لذا هنا تاثير زاوية انحراف البئر على قابلية رفع الصخور سيتم توضيحها في هذه الدراسة. دراسة احصائية تم استخدامها لدراسة قيم قابلية رفع الصخور بوجود زاوية لانحراف البئر مع القيم التي لا تأخذ زاوية انحراف البئر بنظر الاعتبار . النتائج وضحّت بأن زوايا انحراف قليلة لها تأثير ضعيف على قيم قابلية رفع الصخور ، لكن هذه الدراسة يمكن استخدامها على زوايا انحراف عالية مثل الابار المنحرفة و الابار الافقية ، حيث هنا زوايا احراف عالية ستؤدي الى تأثير عالي على قيم قابلية رفع الصخور .

الكلمات الرئيسية: تنظيف البئر، نقل قطع الصخور، قابلية رفع الصخور، زاوية انحراف البئر، سرعة السقوط.

1. INTRODUCTION

Sifferman and Becker ,1992 conducted after 4 – years multifactor experimental study on hole cleaning in inclined wellbores, ten variables were used. They concluded that the variables with significance influence on cuttings transport are mud annular velocity, mud density, inclination angle and drill pipe rotation as well as pipe eccentricity.
The annular velocity of an oil well drilling operation is chosen to transport drill cuttings from the bottom of the well to the surface , meanwhile it must maintain the concentration of cuttings in the annulus within certain limits dictated by the drilling and formation conditions. Using available experimental data, empirical equations describing the setting velocity of the drill cuttings were first determined. Increasing the mud density, creating laminar annular mud flow or rotating the drill pipe may also improve the carrying capacity of mud, **Hopkin, 1967** and **Chain, 1969**.
A simple rig-site graphical technique was presented for determining hole cleaning requirements for a range of hole sizes. This method used a set of charts which had been derived from a computer model based on both laboratory and field measurements. Mud rheologywais shown to be a key variable for optimizing hole cleaning in deviated wells, **Luo, 1994**.
It has been shown that in vertical annuluses, the fluid annular velocity has a major effect on the carrying capacity of muds, while other parameters have an effect only at low to medium fluid annular velocities, **Hussaini** and **Azar, 1983**.
Using the concept of minimum transport velocity, which presumes that a hole can be efficiently cleaned by either maintaining cuttings rolling or in suspension if the annular velocity is equal to or greater than the minimum transport velocity for that operational condition, **Paden** and **Ford, 1990**.
Several experimental studies have been performed to determine the minimum annular velocity required to lift the cuttings, and the results showed that a minimum annular velocity of 50 ft/min is required to provide effective cutting transport for a typical drilling fluid. However the slip velocity of the cuttings determines how effective the cutting transport will be, **Mojisola, 2005**.
Rabia, 2001 showed that for optimum lifting capacity the following factors must be considered:
1- Turbulent flow is most favorable for efficient removal of cuttings.
2- Low viscosity and low gel strength of mud are desirable properties for cuttings removal.
3- High mud density efficiently helps to remove cuttings away from the wellbore.
4- Pipe rotation aids the removal of cuttings.

Jerzy et al., 2013 studied the behavior of the slip velocities in a two-phase (solid and liquid) mixture flow in a vertical pipe. It was noted that the measured slip velocities in the two-phase flow were influenced by the fluctuations in the concentration of the flowing mixture during the measurement. Furthermore, the shape of the cuttings could affect the precision of the measured slip velocities.
Onuoha et al., 2015 illustrated the effect of hole inclination angle on the Cutting Transport Ratio (*CTR*). It was concluded that when using water-base mud as a drilling fluid, the *CTR* found to be decreased when the inclination angle is between 0º and 60º. On the other hand, when using polypropylene beads with water base mud would improve the *CTR*, especially at high inclination angle (i.e. 75º – 90º).
Mohammadsalehi and **Malekzadeh**, **2011** developed a computer program that combines Larson's and Moore models to predict the minimum flow rate of the transported cuttings for the hole inclination angles range from 0º to 90º. For inclination angles between 55º – 90º, the

rheological properties of the drilling mud goes higher causing the flow rate to be decreased, while for higher inclination angles, lower rheological properties of the drilling mud is more favorable to obtain better hole cleaning efficiency.

2. THEORETICAL BACKGROUND

Efficient removal of cuttings from the wellbore is one of the major considerations during both design and operational stages of a drilling process. Inadequate hole cleaning may give rise to serious drilling problems, like increase in torque and drag, stuck pipe, loose control on density, difficultly when running and cementing casing, etc. To avoid such problems, generated cuttings have to be removed from the wellbore by the help of the drilling fluid. The ability of the fluid to lift such cuttings is generally referred to as carrying capacity of the drilling fluid.
Factors affecting the ability of drilling mud to lift cuttings are (1) fluid rheological properties, (2) particle setting velocity, (3) particle size and size distribution, geometry and concentration, (4) penetration rate of drill bits, (5) rotary speed of drill string, (6) fluid density, (7) hole inclination, (8) mud type, (9) drill pipe position and (10) drill pipe size. Simultaneously, the determination of carrying capacity of a mud becomes a complicated problem.

2.1 Cuttings transport parameters:

1- Slip velocity (V_{sl}). Slip velocity is the falling cuttings velocity in the annulus, according to the law of gravity.
2- Cutting velocity (V_{cut}). Cutting velocity is the velocity that must be fulfill by cutting to the surface.
3- Minimum velocity (V_{min}). Minimum velocity is a required velocity of the annular fluid so than the cutting can be transported to the surface.
The mathematical relation is defined as follows, **Indra** and **Rudi, 2002**:

$$V_{cut} = V_{\min} - V_{sl} \tag{1}$$

4- The Cutting Transport Ratio (*CTR*), which is defined as the ratio of the cutting transport velocity over the minimum mean annular velocity as follows:

$$CTR = \frac{V_{cut}}{V_{\min}} = 1 - \frac{V_{sl}}{V_{\min}} \tag{2}$$

A (*CTR*) of 1.0 or 100% implies perfect hole cleaning.
- If *CTR* > 0 cuttings are moving upward.
- *CTR* should be > 0.5 for optimum hole cleaning.

Obviously total removal of drill solids would correspond to a transport ratio of 100 percent, however this degree of efficiency can be difficult to achieve because of practical constraints.

2.1.1 Moore correlation:
Several equations were presented by **Moore, 1974** for the calculations. Reynold's number is calculated from:

$$N_{\mathrm{Re}} = \frac{928\,\rho_f\,V_{sl}\,d_s}{\mu} \tag{3}$$

For Reynold's number greater than 300, the slip velocity can be calculated as follows:

$$V_{sl}(ft/\mathrm{sec}) = 1.54\sqrt{d_s\,.\frac{\rho_s-\rho_f}{\rho_f}} \tag{4}$$

For Reynold's number less than 3, when flow is considered to be laminar, the slip velocity equation becomes:

$$V_{sl}(ft/\mathrm{sec}) = 82.87\,\frac{{d_s}^2}{\mu}\,(\rho_s-\rho_f) \tag{5}$$

For intermediate Reynold's numbers corresponding to the transitional flow regime, slip velocity can be calculated as:

$$V_{sl}(ft/\mathrm{min}) = \frac{174.7\,d_s\,(\rho_s-\rho_f)^{0.667}}{{\rho_f}^{0.333}\,.\,{\mu_e}^{0.333}} \tag{6}$$

2.1.2 Chien correlation:
Chien correlation assumed a general empirical equation for calculating slip velocity as follows, **Chien, 1972**:

$$V_{sl}(ft/\mathrm{min}) = 86.5\left(\frac{d_s(\rho_s-\rho_f)}{\rho_f}\right)^{0.5} \tag{7}$$

Moore correlation is used in normal vertical well to determine these parameters. But in deviated or even horizontal wells Moore correlation cannot be applied. **Indra** and **Rudi , 2002** developed a new correlation for this problem that is used to determine the parameters. The correlations are as follows:

For the case of $\theta < 45^{\circ}$:
where θ represents the hole inclination angle.

$$V_{\mathrm{min}}(ft/\mathrm{min}) = V_{cut}(ft/\mathrm{min}) + \left[\frac{(45+2\theta)(600-N)(3+\rho_f)}{405000}\right]V_{sl}(ft/\mathrm{min}) \tag{8}$$

For $\theta > 45^{\circ}$:

$$V_{\mathrm{min}}(ft/\mathrm{min}) = V_{cut}(ft/\mathrm{min}) + \left[\frac{(600-N)(3+\rho_f)}{3000}\right]V_{sl}(ft/\mathrm{min}) \tag{9}$$

While, V_{cut} is solved as following:

$$V_{cut}\,(ft/\sec) = \frac{ROP}{36\left[1-\left(\frac{d_{pipe}}{d_{hole}}\right)^{2}\right] C_{conc}} \tag{10}$$

V_{cut} should convert to (ft/min) units. Another method to predict the value of cuttings transport ratio assumed by **Darely and Gray, 1988** as follows:

1- Calculating annular velocity (V_{min}) based on flow rate (Q), hole and pipe diameter:

$$V_{\min} = \frac{24.5\,Q}{{d_{hole}}^{2} - {d_{pipe}}^{2}} \tag{11}$$

2- After calculating V_{min} the next step is to use Sifferman's graph by plotting the velocity (V_{min}) to intersect with the type of drilling fluid used where this approach four types of drilling fluids (water, thin mud, intermediate mud and thick mud), and from this intersection , cuttings transport ratio will be determined as shown in **Fig. 1**.

Guo *et al*. (1993) presented an equation to determine the expected cutting size as follows:

$$d_s = \frac{12}{60}\,\frac{ROP}{N} \tag{12}$$

Wolfgang, 2001 submitted another approach to know the cutting size as:

$$d_s = \frac{\tau_g}{10.4\,(\rho_s - \rho_f)} \tag{13}$$

$$\rho_s = \rho_f + \frac{\tau_g}{10.4\,d_s} \tag{13a}$$

where τ_g represents the gel strength required to suspend particle of the cutting diameter.

3. COLLECTION OF DATA

Data was collected from Iraqi South Oil Company. Drill bit records, mud control, and drilling tubular data for five drilled wells in Rumaila field, Southern Iraq were used for the calculations in this study.

4. RESULTS AND DISCUSSION

4.1 Regular calculations (when angle of inclination was not taken under consideration):

4.1.1 Annular velocity calculations:

First of all, the unknown parameters must be determined such as cutting size diameter and cutting density. Taking into consideration that all used parameters must be in homogenous units by using conversion factors. Guo equation, i.e. eq. (12) is used to compute cutting size diameter (d_s). To calculate cutting density (ρ_s) equation (13a) is used, where τ_g in eq.(13) represents the highest reading of zero gel or 10 min. gel, **Lee *et al.* 2004**.
Both computed cutting size diameter and cutting density are tabulated in Tables (1), (2) , (3) , (4) and (5) for wells Ru-273 , Ru-301 , Ru-285 , Ru-283 and Ru-281 respectively. Surprisingly, some of the calculated cutting density exhibits high values. This might be attributed to the inexact estimation of the cuttings size as there is no perfect approach for the cutting size estimation.
The next step of calculations is annular velocity computation using equation (11) and its results were tabulated in Tables (6), (7), (8), (9) and (10). The computed annular velocity is used to determine cutting transport ratio (*CTR*) by Sifferman's graph, **Fig.1**. This approach is considered the quickest, but not the most accurate method of *CTR* determination. The determined values of cutting transport ratio (*CTR*) by Sifferman's graph are tabulated in Tables (6), (7), (8), (9) and (10). It is noticed from Sifferman's graph that this method Is extremely limited to fixed types of drilling fluid properties such as μ_p , Y_p , zero min. gel and 10 min. gel for four types of fluids. Furthermore, it is noted that for high values of flow rate (Q), there is considerable corresponding values for *CTR*, whereas low Q values produced unknown *CTR* values as shown in Tables 6-10.
The computed values of annular velocities by eq. (11) are used later beside the slip velocity to compute cutting transport ratio (*CTR*) by using eq. (2).
According to **Rabia, 2001**, hole cleaning will be efficient if annular velocity V_a or $V_{min.}$ must be greater than slip velocity V_s and it is observed that at annular velocities of less than 100 ft/min. , particle slip velocity in both Newtonian and non-Newtonian fluids is independent of the fluid annular velocity. Above an annular velocity of 100 ft/min., there appears to be a dependence of slip velocity on annular velocity.

4.1.2 Slip velocity calculations:

According to **Rabia, 2001**, the type of flow considered for slip velocity calculations will be chosen to be transitional (between laminar and turbulent), because the type of flowing is unknown. Using power-law model equations:

$$n = 3.32 \log\left(\frac{\phi_{600}}{\phi_{300}}\right) \quad (14)$$

The following equations are so useful for k, μ_p and Y_p calculations:

$$\mu_p = \phi_{600} - \phi_{300} \quad (15), \qquad \phi_{600} = \mu_p + \phi_{300} \quad (15a)$$

$$Y_p = \phi_{300} - \mu_p \quad (16), \qquad \phi_{300} = Y_p + \mu_p \quad (16a)$$

$$K = \frac{\phi_{300}}{(511)^{n}} \tag{17}$$

$$\mu_e = \left[\frac{2.4 * V_a * (2n+1)}{(D_h - OD_p * 3n} \right]^n * \frac{200K(D_h - OD_p)}{V_a} \tag{18}$$

$$V_{sl}\ (ft/\min) = 174.7\ \frac{d_{pipe} * (\rho_s - \rho_f)^{0.667}}{\rho_f^{\ 0.333} * \mu_e^{\ 0.333}} \tag{19}$$

$$C_{conc.}\ (\%) \ = \ \frac{1}{60}\ \frac{ROP * D_h^{\ 2}}{(V_a - V_{sl})(D_h^{\ 2} - OD_p^{\ 2})} \tag{20}$$

From the given data the parameters φ_{300}, φ_{600} , n, K, μ_e and V_{sl} are computed using Equations (16a),(15a),(14),(17),(18) and (19) respectively. Later, *CTR* and $C_{conc.}$ will be computed using equations (2) and (20) respectively.
The results of the used equations above were tabulated in Tables (11), (12), (13), (14) and (15) for wells Ru-273 , Ru-301 , Ru-285 , Ru-283 and Ru-281 respectively .
All the previous calculations were done when the angle of inclination was not considered.

4.2 Calculations when small angles of inclination were considered (semi vertical well):

4.2.1 Cutting velocity calculation:
By getting the benefit of C_{conc} values computed from above equations, cutting velocity will be computed using equation (10). The resulted cutting velocity will be in units of ft/sec. and should be converted to units of ft/min.

4.2.2 Annular velocity calculations:
For the case of inclination, annular velocity will be calculated using equation (8), because the data given were exclusive for the case of angle of inclination ($\theta < 45^{\circ}$).
Slip velocity values computed above when angle of inclination was not under consideration will be used altogether with the computed values of V_{mim} and $V_{cut(inc.)}$ for case of inclination to calculate *CTR* values for case of inclination. The resulted values were tabulated in Tables (16), (17), (18), (19) and (20) for wells Rumaila-273, Rumaila -301, Rumaila -285, Rumaila -283 and Rumaila -281 respectively. It is noted that, some values of slip velocities were obtained due to the uncertain method of cutting size determination. Cutting size (d_s) affect the slip velocity (V_{sl}) and consequently Cutting Transport Ratio (*CTR*).

4.3 Figures interpretation:

From the obtained results, plotting depth vs. Cuttings Transport Ratio (*CTR*) for three cases (Normal, Sifferman's and inclined).
Figures 2-6 represent the plot of *CTR* vs. depth for wells Rumaila -273, Rumaila -301, Rumaila -285, Rumaila -283 and Rumaila -281 respectively.

From these figures, it has been realized that Sifferman's method gave an approximate values of *CTR* i.e. not accurate as the other methods mentioned above. Furthermore, the methods applied in this study when small angles of inclination are considered also gave some abnormal values which confirm that there is no ideal method of the *CTR* determination when the case of inclination angle is considered.
In addition, Figures 2-6 plotted showed that the inclination angles hence were so low and near to 1° or less (vertical wells) subsequently it had a slight effect on *CTR* calculated values that took angle of inclination into consideration, but when the angle of inclination increases, it is supposed that it gives higher effect on calculated *CTR* values and that point is extremely clear for inclined wells (deviated wells) and horizontal wells where the effect of gravity is obvious.

4.4 Statistical study of normal and inclined values of CTR:

The Paired-Samples T- test procedure compares the means of two variables for a single group. It computes the differences between values of the two variables for each case and tests whether the average differs from 0.

Statistics: For each variable: mean, sample size, standard deviation, and standard error of the mean. For each pair of variables: correlation, average difference in means, t test, and confidence interval for mean difference standard deviation and standard error of the mean difference will be determined as shown below by using SPSS program :

T-test for well Rumaila-273

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	CTR_NOR	94.964125	4	5.062440	2.531220
	CTR_INC	96.184533	4	3.660406	1.830203

Paired Samples Correlations

	N	Correlation	Sig.
Pair 1 CTR_NOR & CTR_INC	4	.998	.002

Paired Samples Test

	Paired Differences					t	df	Sig. (2-tailed)
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1 CTR_NOR - CTR_INC	-1.220408	1.430310	.715155	-3.496350	1.055535	-1.706	3	.186

T-test for well Rumaila -301

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	CTR_NOR	93.228835	4	4.095601	2.047801
	CTR_INC	94.927175	4	2.840964	1.420482

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	CTR_NOR & CTR_INC	4	.998	.002

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	CTR_NOR - CTR_INC	-1.698340	1.276486	.638243	-3.729515	.332835	-2.661	3	.076

T-test for well Rumaila -285

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	CTR_NOR	91.375008	4	7.571113	3.785557
	CTR_INC	93.521985	4	5.441166	2.720583

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	CTR_NOR & CTR_INC	4	.999	.001

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	CTR_NOR - CTR_INC	-2.146978	2.145157	1.072579	-5.560401	1.266446	-2.002	3	.139

T-test for well Rumaila -283

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	CTR_NOR	89.538175	4	7.126445	3.563223
	CTR_INC	91.980903	4	5.338956	2.669478

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	CTR_NOR & CTR_INC	4	.999	.001

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	CTR_NOR - CTR_INC	-2.442728	1.800726	.900363	-5.308084	.422629	-2.713	3	.073

T-test for well Rumaila -281

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	CTR_NOR	92.565325	4	5.744746	2.872373
	CTR_INC	94.328388	4	4.264596	2.132298

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	CTR_NOR & CTR_INC	4	1.000	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	CTR_NOR - CTR_INC	-1.763063	1.484251	.742125	-4.124837	.598711	-2.376	3	.098

As shown above from the statistical correlation between normal *CTR* and inclined *CTR* the difference between standard deviation for both normal and inclined *CTR* are relatively low also , the same thing applied on the difference between standard error mean and that means that the values of *CTR* are approximate and subsequently it means that the effect of angle of inclination on inclined *CT*R values had slightly effect, because the angle of inclination does not exceed 1.75° but it is reasonable that when the angle of inclination is high and that reflects on the values of *CTR* for inclination and subsequently the difference between normal *CT*R and inclined *CTR* will be high and the analysis for that case will be absolutely different especially for deviated and horizontal wells.

5 CONCLUSIONS

1- From the obtained results of *CTR* during the case of inclination, the hole inclination angle has slight effect on *CTR* values, especially for angles less than 1°, whereas for inclination angles greater than 1°, the *CTR* values seemed to be slightly decreased.
2- For shallow depths, high rate of penetration values are used to achieve maximum drilling efficiency leading to high cuttings concentration and consequently low *CTR*, i.e. *CTR* values are inversely proportional with cuttings concentration.
3- In general, low inclination angles taken in the present study did not show clearly an effective influence on the *CTR* values. Further investigation for high inclination angles i.e. (derived or horizontal wells) is required for future studies.
4- The calculations obtained in this study when small values of inclination angles are considered showed abnormal values of cutting density, slip velocity, minimum annular velocity and cutting transport ratio due to the inexact determination of cutting size. Accurate determination of the cutting size is required to give more precise results.

NOMENCLATURE

$C_{conc.}$: cutting concentration, percentage.
CTR : cutting transport ratio ,percentage or fraction.
d_{hole} or D_h : hole diameter ,in..
d_{pipe} or OD_p : pipe outside diameter ,in.
d_s : cutting diameter ,in.
N : rotary speed ,RPM.
$N_{Re:}$ reynold's number, dimensionless.
Q : flow rate ,gal./min.
ROP : rate of penetration ,ft/hr.
V_{cut} : cutting transport velocity ,ft/sec.
$V_{min.}$: minimum annular velocity ,ft/min.
V_{sl} : slip velocity ,ft/min
Y_p : yield point (lb/100ft^2).
θ : angle of inclination ,degree.
μ_a : apparent viscosity c.p.
μ_e : effective viscosity ,c.p.
μ_p : plastic viscosity c.p.
ρ_f *or* ρ_m : fluid mud density ,lb/gal..
ρ_s : cutting density ,lb/gal.
τ_g : gel strength ,lb/100ft^2.
Φ_{300} : dial reading @ 300 rpm.
Φ_{600} : dial reading @ 600 rpm.

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Table 1. Parameters of well Rumaila -273.

Depth (m)	**Specific gravity**	**ρ_f (lb/gal)**	**τ_g (lb/100ft^2)**	**ROP (m/hr)**	**ROP (ft/hr)**	**N (rpm)**	**d_s (in.)**	**ρ_s (lb/gal)**
525	1.08	8.9964	10	9.495	31.153	100	0.0623	24.43
1917	1.17	9.7461	17	1.7662	5.795	80	0.0144	123.15 **(abnormal value)**
2332	1.22	10.162	5	1.454	4.77	70	0.0136	45.5
2395	1.19	9.9127	5	4.666	15.31	60	0.051	10.61

Table 2. Parameters of well Rumaila -301.

Depth (m)	**Specific gravity**	**ρ_f (lb/gal)**	**τ_g (lb/100ft^2)**	**ROP (m/hr)**	**ROP (ft/hr)**	**N (rpm)**	**d_s (in.)**	**ρ_s (lb/gal)**
460	1.06	8.8298	8	12.74	41.914	100	0.0838	18.004
1850	1.14	9.4962	8	2.61	8.5869	70	0.0245	40.875
2296	1.17	9.7461	15	2.28	7.501	80	0.0187	86.831 **(abnormal value)**
2346	1.18	9.8294	14	2.3	7.567	50	0.0302	54.379

Table 3. Parameters of well Rumaila -285.

Depth (m)	**Specific gravity**	**ρ_f lb/gal)**	**τ_g (lb/100ft^2)**	**ROP (m/hr)**	**ROP (ft/hr)**	**N (rpm)**	**d_s (in.)**	**ρ_s (lb/gal)**
461	1.07	8.9131	16	15.36	50.534	90	0.112	22.641
1850	1.12	9.3296	12	3.48	11.449	60	0.038	39.676
2288	1.17	9.7461	10	2.89	9.508	80	0.023	51.528
2358	1.15	9.5795	10	6	19.74	50	0.0789	21.759

Table 4. Parameters of well Rumaila -283.

Depth (m)	**Specific gravity**	**ρ_f (lb/gal)**	**τ_g (lb/100ft^2)**	**ROP (m/hr)**	**ROP (ft/hr)**	**N (rpm)**	**d_s (in.)**	**ρ_s (lb/gal)**
503	1.08	8.996	15	10.93	35.959	80	0.0898	25.048
1918	1.14	9.496	14	3.29	10.824	80	0.027	59.325
2325	1.17	9.7461	14	2.89	9.508	80	0.0237	66.513 **(abnormal value)**
2378	1.15	9.579	12	4.9	16.121	50	0.0645	27.458

Table 5. Parameters of well Rumaila -281.

Depth (m)	**Specific gravity**	**ρ_f (lb/gal)**	**τ_g (lb/100ft^2)**	**ROP (m/hr)**	**ROP (ft/hr)**	**N (rpm)**	**d_s (in.)**	**ρ_s (lb/gal)**
500	1.08	8.996	16	10.17	33.459	80	0.0836	27.388
1955	1.15	9.579	14	3.6	11.844	60	0.0395	36.355
2377	1.18	9.829	11	3.28	10.791	80	0.0269	49.126
2421	1.15	9.579	14	2.8	9.212	50	0.0367	46.1

Table 6. Annular velocity calculations of well Rumaila -273.

Depth (m)	**Q (L/min.)**	**Q (gal/min.)**	**d_{hole} (in.)**	**OD_{pipe} (in.)**	**V_{min} (ft/min)**	**CTR by Siff. graph (%)**
525	2000	528.36	17.5	5	46.026	near 78%
1917	1400	369.81	12.25	5	72.446	near 91%
2332	1500	396.225	8.5	5	205.45	unknown
2395	760	200.754	6	3.5	207.093	unknown

Table 7. Annular velocity calculations of well Rumaila -301.

Depth (m)	**Q (L/min.)**	**Q (gal/min.)**	**d_{hole} (in.)**	**OD_{pipe} (in.)**	**V_{min} (ft/min)**	**CTR by Siff. graph (%)**
460	2250	594.337	17.5	5	51.773	near 79.5%
1850	1200	316.98	12.25	5	62.097	near 84%
2296	1500	396.225	8.5	5	205.45	unknown
2346	825	217.923	5.875	3.5	239.798	unknown

Table 8. Annular velocity calculations of well Rumaila -285.

Depth (m)	Q (L/min.)	Q (gal/min.)	d_{hole} (in.)	OD_{pipe} (in.)	V_{min} (ft/min)	CTR by Siff. graph (%)
461	2287	604.111	17.5	5	52.624	near 79%
1850	1220	322.263	12.25	5	63.1319	near 83.5%
2288	1525	402.828	6	3.5	415.548	unknown
2358	838	221.357	6	3.5	228.347	unknown

Table 9. Annular velocity calculations of well Rumaila -283.

Depth (m)	Q (L/min.)	Q (gal/min.)	d_{hole} (in.)	OD_{pipe} (in.)	V_{min} (ft/min)	CTR by Siff. graph (%)
503	2135	563.96	17.5	5	49.127	near 79.5%
1918	1830	483.394	12.25	5	94.6978	near 93%
2325	1448	382.489	8.5	5	198.327	unknown
2378	750	198.112	6	3.5	204.368	unknown

Table 10. Annular velocity calculations of well Rumaila -281.

Depth (m)	Q (L/min.)	Q (gal/min.)	d_{hole} (in.)	OD_{pipe} (in.)	V_{min} (ft/min)	CTR by Siff. graph (%)
500	2240	591.696	17.5	5	51.543	near 81%
1955	1982	523.545	12.25	5	102.5635	near 97%
2377	1525	402.828	8.5	5	208.873	Unknown
2421	780	206.037	6	3.5	212.543	Unknown

Table 11. Slip velocity and cuttings transport ratio calculations of well Rumaila -273.

Depth (m)	d_{hole} (in.)	OD_{pipe} (in.)	Φ_{300}	Φ_{600}	n	K	μ_e (c.p)	V_{sl} (ft/min)	CTR (%)	$C_{conc.}$ (%)
525	17.5	5	22	30	0.447	1.353	227.172	5.335	88.409	1.389
1917	12.25	5	24	30	0.322	3.227	213.053	4.639	93.597	0.171
2332	8.5	5	22	32	0.540	0.757	42.766	3.389	98.351	0.060
2395	6	3.5	20	30	0.585	0.522	31.486	1.035	99.500	0.188

Table 12. Slip velocity and cuttings transport ratio calculations of well Rumaila -301.

Depth (m)	d_{hole} (in.)	OD_{pipe} (in.)	Φ_{300}	Φ_{600}	n	K	μ_e (c.p)	V_{sl} (ft/min)	CTR (%)	$C_{conc.}$ (%)
460	17.5	5	44	30	0.6517	0.481	115.433	6.395	87.649	1.676
1850	12.25	5	50	30	0.689	0.421	87.041	4.553	92.667	0.298
2296	8.5	5	58	32	0.728	0.373	50.8178	7.505	96.347	0.0966
2346	5.875	3.5	52	30	0.7	0.407	41.282	8.985	96.253	0.085

Table 13. Slip velocity and cuttings transport ratio calculations of well Rumaila -285.

Depth (m)	d_{hole} (in.)	OD_{pipe} (in.)	Φ_{300}	Φ_{600}	n	K	μ_e (c.p)	V_{sl} (ft/min)	CTR (%)	$C_{conc.}$ (%)
461	17.5	5	26	38	0.547	0.857	164.922	9.899	81.190	2.147
1850	12.25	5	27	39	0.530	0.989	130.613	6.068	90.388	0.401
2288	6	3.5	40	65	0.700	0.508	44.435	6.416	98.456	0.059
2358	6	3.5	26	40	0.621	0.540	37.755	10.270	95.503	0.229

Table 14. Slip velocity and cuttings transport ratio calculations of well Rumaila -283.

Depth (m)	d_{hole} (in.)	OD_{pipe} (in.)	Φ_{300}	Φ_{600}	n	K	μ_e (c.p)	V_{sl} (ft/min)	CTR (%)	$C_{conc.}$ (%)
503	17.5	5	40	65	0.700	0.508	136.632	9.350	80.967	1.641
1918	12.25	5	25	36	0.526	0.942	101.311	6.493	93.143	0.245
2325	8.5	5	28	42	0.585	0.731	51.611	7.716	96.109	0.127
2378	6	3.5	22	32	0.540	0.757	36.725	10.946	94.644	0.211

Table 15. Slip velocity and cuttings transport ratio calculations of well Rumaila -281.

Depth (m)	d_{hole} (in.)	OD_{pipe} (in.)	Φ_{300}	Φ_{600}	n	K	μ_e (c.p)	V_{sl} (ft/min)	CTR (%)	$C_{conc.}$ (%)
500	17.5	5	40	60	0.585	1.044	218.962	8.146	84.195	1.399
1955	12.25	5	30	46	0.616	0.643	89.583	6.518	93.645	0.247
2377	8.5	5	38	58	0.610	0.848	65.981	6.297	96.985	0.136
2421	6	3.5	29	46	0.665	0.458	41.069	9.699	95.436	0.115

Table 16. Cutting velocity, annular velocity and cuttings transport ratio calculations for case of inclination for well Rumaila -273.

Depth (m)	V_{cut} (ft/sec)	V_{cut} (ft/min)	Angle of inc.(θ), Degree	V_{min} (ft/min)	CTR for inclination , (%)
525	0.678	40.691	1	44.405	91.637
1917	1.130	67.807	1.75	71.489	94.849
2332	3.368	202.061	1	204.805	98.661
2395	3.434	206.058	1.25	206.905	99.591

Table 17. Cutting velocity, annular velocity and cuttings transport ratio calculations for case of inclination for well Rumaila -301.

Depth (m)	V_{cut} (ft/sec)	V_{cut} (ft/min)	Angle of inc.(θ), Degree	V_{min} (ft/min)	CTR for inclination , (%)
460	0.7563	45.379	1	49.768	91.1803
1850	0.9591	57.544	1	61.043	94.268
2296	3.299	197.945	0.25	203.533	97.254
2346	3.847	230.813	0.25	237.936	97.006

Table 18. Cutting velocity, annular velocity and cuttings transport ratio calculations for case of inclination for well Rumaila -285.

Depth (m)	V_{cut} (ft/sec)	V_{cut} (ft/min)	Angle of inc.(θ), Degree	V_{min} (ft/min)	CTR for inclination , (%)
461	0.712	42.726	0.25	49.482	86.345
1850	0.951	57.064	0.5	61.653	92.557
2288	6.819	409.132	0.75	414.015	98.821
2358	3.637	218.077	0.75	226.235	96.394

Table 19. Cutting velocity, annular velocity and cuttings transport ratio calculations for case of inclination for well Rumaila -283.

Depth (m)	V_{cut} (ft/sec)	V_{cut} (ft/min)	Angle of inc.(θ), Degree	V_{min} (ft/min)	CTR for inclination , (%)
503	0.663	39.777	0.5	46.4015	85.723
1918	1.47	88.204	1	93.101	94.741
2325	3.177	190.611	0.5	196.42	97.043
2378	3.224	193.422	0.5	202.023	95.742

Table 20. Cutting velocity, annular velocity and cuttings transport ratio calculations for case of inclination for well Rumaila -281.

Depth (m)	V_{cut} (ft/sec)	V_{cut} (ft/min)	Angle of inc.(θ), Degree	V_{min} (ft/min)	CTR for inclination , (%)
500	0.723	43.397	0.75	49.231	88.149
1955	1.601	96.046	0.5	101.074	95.0249
2377	3.376	202.577	0.25	207.296	97.723
2421	3.381	202.844	0.25	210.383	96.417

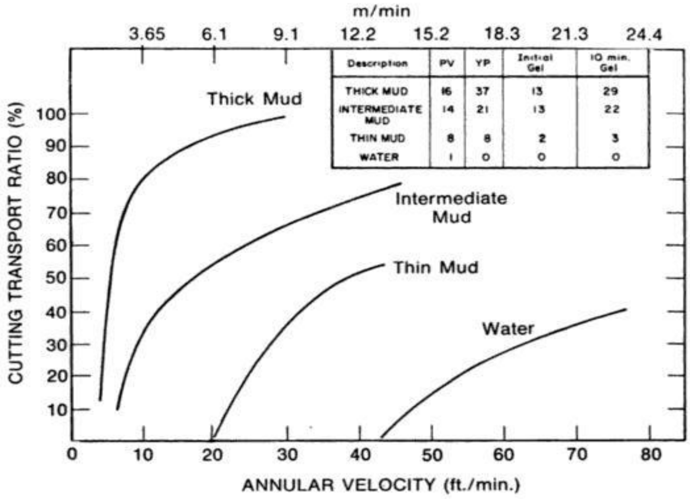

Figure 1. Sifferman's graph for cutting transport ratio determination

(**Sifferma**n and **Becker, 1992**).

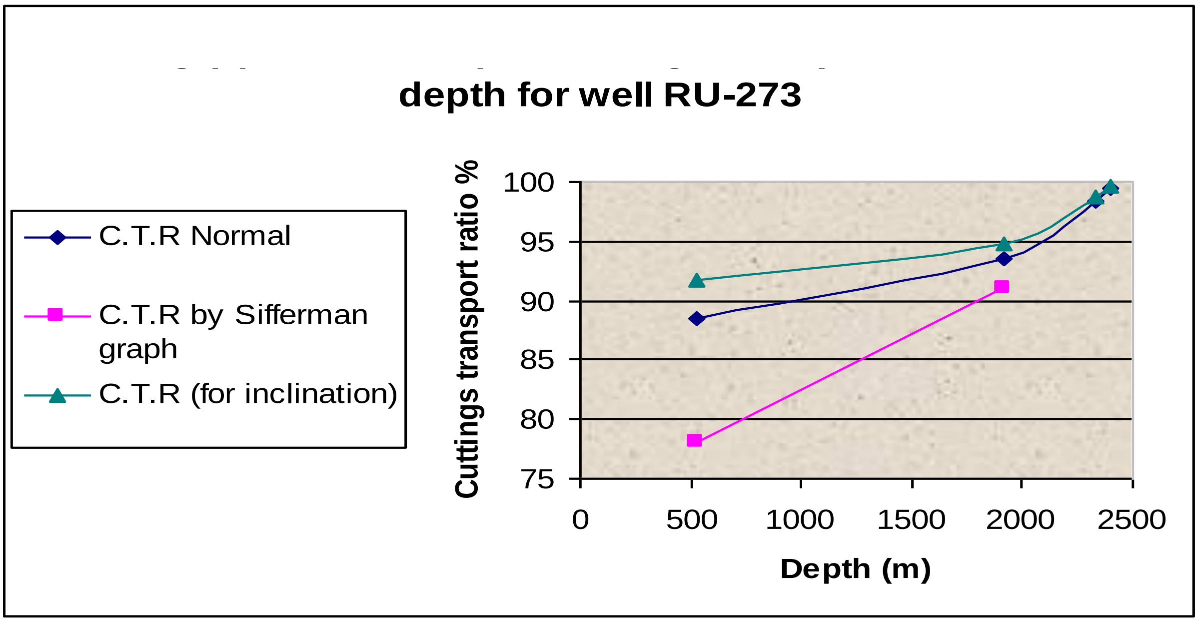

Figure 2. Relationship of cuttings transport ratio vs. depth for well Rumaila -273.

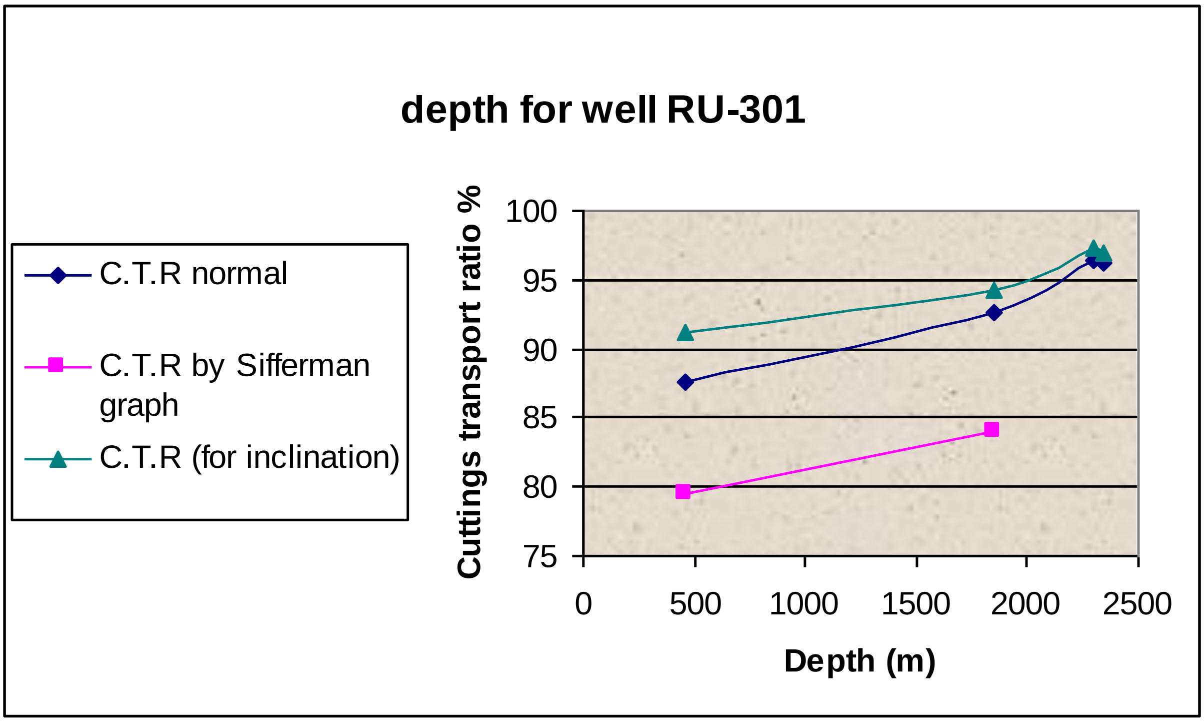

Figure 3. Cuttings Transport Ratio (*CTR*) vs. depth for well Rumaila -301.

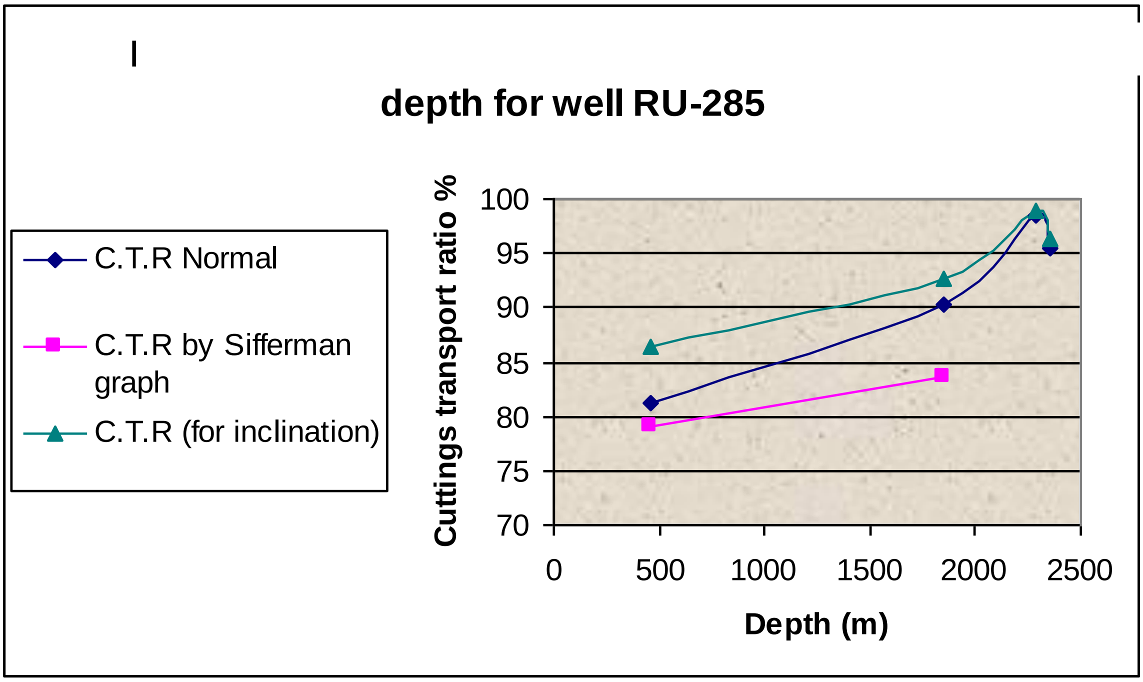

Figure 4. Cuttings Transport Ratio (*CTR*) vs. depth for well Rumaila -285.

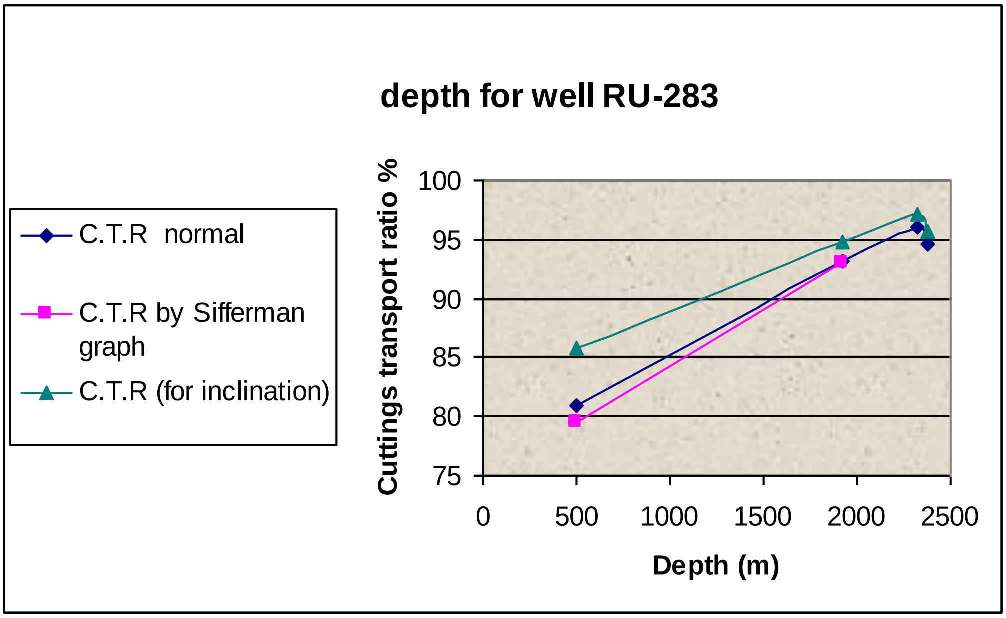

Figure 5. Relationship of cuttings transport ratio vs. depth for well Rumaila -283.

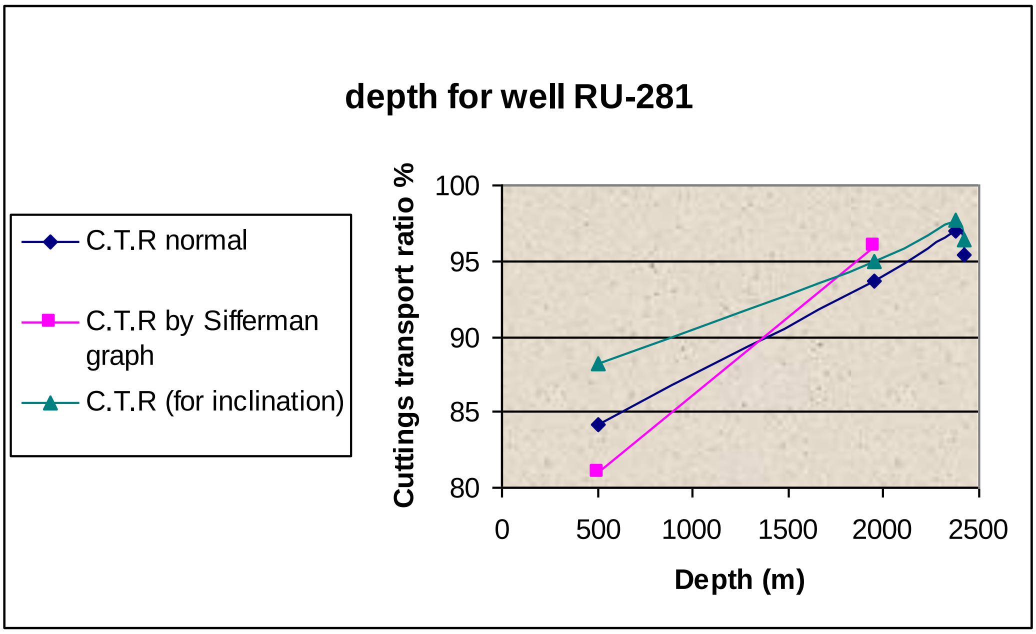

Figure 6. Relationship of cuttings transport ratio vs. depth for well Rumaila -281.