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Effect of Hole Cleaning on Drilling Rate and Performance

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Abstract

Drilling rate depends upon weight on the drill bit, the rotary speed, and the pressure differential across the bottom of the hole. Equation 1 describes the mathematical relationship:

$$ROP = \frac{CW^2 N^l}{m + \Delta P} \qquad \text{equation 1}$$

Where C is a drillability constant,
W is the weight on bit, in lbs;
N is the rotary speed of the bit, in rpm; and
m and ? are constants,

The pressure differential (? P) is the difference between the pressure at the bottom of the hole while drilling and the formation pressure. Bottom hole pressure is the sum of the pressure created by the mud weight, the pressure drop in the annulus from drilling fluid circulation, and the cuttings in the annulus. The annular pressure is called Equivalent Circulating Density (ECD). In this paper, only the mud weight and the cuttings in the annulus will be used to calculate the changes in pressure differential across the bottom of the hole. Annular pressure losses from drilling fluid flow are assumed to be constant – and the accuracy of current calculations is considered insufficient to include in this calculation procedure.

The cuttings in the annulus depends upon the drilling rate (the rate at which cuttings enter the annulus) and the carrying capacity of the drilling fluid.

The carrying capacity of drilling fluid can be estimated from the carrying capacity index (CCI), equation 2.

$$CCI = \frac{K(AV)(MW)}{400{,}000} \qquad \text{equation 2}$$

Where:
AV is the annular velocity, in ft/min,
MW is the mud weight, in ppg, and
K is a Power Law Constant, in eff.cp.
The Power Law constant can be calculated from equation 3.

$$K = (511)^{1-n}(PV + YP) \qquad \text{equation 3}$$

$$n = 3.322 \log \frac{(2PV + YP)}{(PV + YP)} \qquad \text{equation 4.}$$

Equation 2 is an empirical relationship that seems to indicate whether cuttings are tumbled in the annulus or being carried to the surface in a timely manner. When the CCI = 1, cuttings have a sharp edge and exhibit little grinding or tumbling action in the annulus. The quantity of cuttings in the annulus, however, is not indicated by the CCI. Sifferman published a laboratory study of cuttings transport and measured the quantity of solids in the annulus relative to the input volume. CCI can be correlated with the Transport Ratio.

Application of the concept of correlating hole cleaning indicators with drilling rate

To illustrate the concept, data from a well that was drilled a couple of years ago will be used to compare poor hole cleaning with good hole cleaning. The well conditions are listed below:

12.3 ppg Mud weight; 18.4% volume total solids
5%vol drilled solids
2%vol bentonite
11.4%vol barite
500gpm flow rate
Initial Drilling Rate: 60 ft/hr
16”casing set to 3086’- 14.688” ID
Open 12 ¼” hole to 10,994’
5” drill pipe
852’ of 8” drill collars
Formation pressure constant (gas bearing shale with about 1% volume porosity)

Annular velocities:

Drill collar X open hole	142 ft/min
Drill pipe X open hole	98 ft/min
Drill pipe X casing	64.3 ft/min

Bottoms up time: 126 minutes
Total annular volume 63002 gallons
Initial formation pressure 7032 psi
Initial bottom hole pressure 6832 psi

Initial Conditions

Mud Weight	12.3	ppg
Vb	11.4	%vol
Vds	5	%vol
Vb	2	%vol
Vlg	7	%vol
Flowrate	500	gpm
Hole Volume	6.125	gal/ft
Area [DP X casing]	149.80	
Area [DP X casing]	98.22	hole
Area [DC X hole]	30.63	
PV	18	cp
YP	12	lb/100sqft
K		eff.cp
CCI	0.44	
n	0.68	
K	223.36	eff.cp
Transport Ratio	0.40	
Annular Velocity	64.25	
Annular Velocity	97.99	
Annular Velocity	314.23	

Initial Conditions

Mud Weight	12.3	ppg
Vb	11.4	%vol
Vds	5	%vol
Vb	2	%vol
Vlg	7	%vol
Flowrate	500	gpm
Hole volume	6.13	gal/ft
Area [DP X casing]	149.80	
Area [DP X casing]	98.22	hole
Area [DC X hole]	30.63	
PV	18	cp
YP	20	lb/100sqft
K		eff.cp
CCI	1.17	
n	0.56	
K	592.93	eff.cp
Transport Ratio	1.00	
Annular Velocity	64.25	
Annular Velocity	97.99	
Annular Velocity	314.23	

Calculations

Mud Weight:

The effect of drilled solids in the annulus on mud weight and on drilling rate will be developed with an iterative process. Intervals of 6 minutes were selected. Drilling at 60 ft/hr (or 1 foot per minute) causes the 12 ¼" bit to make 6 feet of hole in 6 minutes. The volume of hole drilled is 6.12 gallons per foot. If the rock has no porosity, 36.72 gallons of rock would enter the drilling fluid. If the rock has a porosity of 20%, only 29.38 gallons of rock would enter the drilling fluid for each 36.72 gallons of hole generated.

The quantity of rock entering the drilling fluid determines the drilling fluid weight. In these calculations the density of low gravity solids is assumed to be 2.6 gm/cc and the density of barite is assumed to be 4.2 gm/cc.

$$\mathrm{Vlg} = 62.5 + 2.0\ \mathrm{Vs} - 7.5\ \mathrm{MW} \qquad \text{Equation 5}$$

Where:
Vlg is the volume percent low gravity solids, which consists of drilled solids and bentonite.
Vs is the volume percent total solids (barite and low gravity solids).

Since this drilling fluid weighs 12.3 ppg with 7% volume low gravity solids, the volume percent of total solids is 18.4% volume. As solids are added from the drilling process, the quantity of barite remains constant but the low gravity solids increase. The addition of drilled solids and the creation of new volume with drilling changes the concentration of barite slightly. The volume of the annulus is 63002 gallons and the additional volume drilled during the 6 minute interval is only about 37 gallons; so the change in volume will be ignored. The barite concentration will be assumed to be constant at 11.4% volume. Equation 5 can be used to calculate the mud weight.

$$\mathrm{MW} = \frac{85.3 + \mathrm{Vlg}}{7.5} \qquad \text{Equation 6}$$

At each interval the quantity of drilled solids generated is added to the volume of drilled solids calculated for the preceding interval. The volume of bore hole is calculated by adding the volume of new hole to the volume calculated in the preceding interval. A ratio of the total drilled solids in the annulus to the volume of the annulus determines the new drilled solids concentration. With the new concentration of drilled solids, Vds, and assuming the bentonite concentration remains 2%volume, the mud weight in the annulus may be calculated from equation 7.

$$MW = \frac{87.3 + Vds}{7.5} \qquad \text{Equation 7}$$

After 126 minutes, the first interval arrives at the surface. With perfect carrying capacity, all of the solids drilled during the first interval would be removed during the next six minute interval. With a 50% transport ratio, only half of the solids would be contained in that 3000 gallons of drilling fluid that arrives at the surface. The other half of the solids would remain in the annulus. The quantity of solids in the well bore before bottoms-up reaches the surface is the same no matter what the carrying capacity is. After bottoms-up, the solids remaining in the annulus depends upon the carrying capacity or the transport ratio.

Calculating volume of solids entering system:

As each interval is drilled, the differential pressure across the bottom of the hole increases because the formation solids added to the annulus. The formation pressure is assumed to be constant because this is a gas-bearing formation. If the pore space was filled with salt water or oil, the pore pressure would increase according to the hydrostatic gradient within the rock. The porosity of the formation was also selected to be very low (1% volume) so that the volume of rock entering the well bore is the same as the volume of hole generated. If the porosity was 20% volume, the volume of the system would increase by the volume of hole drilled but the drilled solids added would be only 80% of the hole volume.

Calculating bottom hole pressure:

As the solids enter the system, the bottom hole pressure may be calculated with either of two methods. The hydrostatic pressure from the column of original fluid can be added to the hydrostatic pressure of the column of drilled solids laden fluid. The solids can also be assumed to be part of the total solids in the annulus and the hydrostatic pressure calculated from the mixture. The latter system is easier to calculate and was selected as the method to determine the pressure at the bottom of the hole using equation 8.

Calculating drilling rate:

The drilling rate when the process started was assumed to be 60ft/hr. With the drilling rate equation presented in equation some constants can be calculated. The weight on bit and rotary speed are assumed to be constant. The “m” constant for typical formations is assumed to be 300. Values from 200 to 400 have been calculated from drilling rate data reported in the literature. Obviously, the data for differential pressure tests must come from laboratory experiments where the formation pressures and bottom hole pressures can be controlled and measured. Including this data into equation 1, the penetration rate can be calculated from equation 8.

$$ROP = \frac{30{,}000}{300 + \Delta P} \qquad \text{Equation 8}$$

The drilled solids circulated up the annulus, increases the pressure differential causes the next interval to drill slower. At each interval the drilling rate is calculated and the footage drilled during the next 6 minute period calculated. The volume of these solids are added to the total drilled solids in the annulus. The total drilled solids in the annulus is divided by the total volume of the annulus which is the original volume plus the new volume drilled.

This process continues until the first interval reaches the surface. At that time, some of the solids drilled in the first interval are discarded and some remain in the annulus. The quantity of drilled solids discarded would be represented by the transport ratio. The quantity remaining would be calculated from 100 minus the transport ratio. Discards of each successive drilled interval (each 6 minutes) are removed until the second bottoms up occurs. The first bottoms-up happens after 126 minutes of circulation; the second bottoms-up happens after 352 minutes of circulation. When the second bottoms up reach the surface, some of the first interval drilled is discarded along with the fraction of solids contained in the 22nd drilled interval will be discarded again according to the transport ratio.

With good hole cleaning (transport ratio = 100%), drilling rate decreases until the first drilled solids reach the surface. As the first drilled solids are removed, bottom hole pressure still increases but at a slower rate. As more solids are removed from the hole because of good carrying capacity, bottom hole pressure starts decreasing. The first solids arrive at the surface when the bit passes 11100 ft. The rate of penetration decreases more slowly until the bit reaches about 11200 ft. At this point sufficient drilled solids are being removed so that the drilling rate actually increases, Figure 2.

With poor hole cleaning (transport ratio = 40%), drilled solids continue to increase in the annulus and the drilling rate fails to show significant abrupt changes. This effect is shown in terms of the pressure differential as the hole is drilled Figure 3.

Conclusions:

Changing the drilling fluid properties to improve hole cleaning has little effect on the pressure differential across the bottom of the hole until the first interval drilled solids arrive at the surface. After this point, the quantity of solids removed from the annulus obviously depends upon the ability to bring drilled solids to the surface.

In the particular example selected, after drilling for a period of time that allows two complete circulations of bottoms-up, the drilling rate for good hole cleaning was 45 ft/hr and for poor hole cleaning was 37 ft/hr. This 8 ft/hr deficit could easily be changed by increasing the yield point of the drilling fluid from 12 to 20 lb/100 sq.ft.

The need to clean cuttings from an annulus has been known for many years. Actually, legend reports the first Spindletop well required some additions to the water circulated to move cuttings from the bottom of the hole to the surface. Supposedly, the driller noticed cattle making a mud puddle and selected that fluid because it looked “thicker” than regular water. Also, hay was added to give the fluid some more “body”. Specifications for drilling fluid are a little more sophisticated now but the requirement to bring cuttings to the surface is still needed. The reason usually given for removing cuttings from the annulus relates to preventing problems. This paper indicates that there is a drilling rate consequence also. Perhaps more consideration should be given to examining cuttings at the shale shaker while drilling. Sharp edges usually indicate good carrying capacity; rounded edges usually means poor carrying capacity. Adjust drilling fluid properties and/or use viscous sweeps to remove cuttings from the vertical, or near, vertical wells. Good carrying capacity should create drilling rate improvements should be as well prevent hole problems.

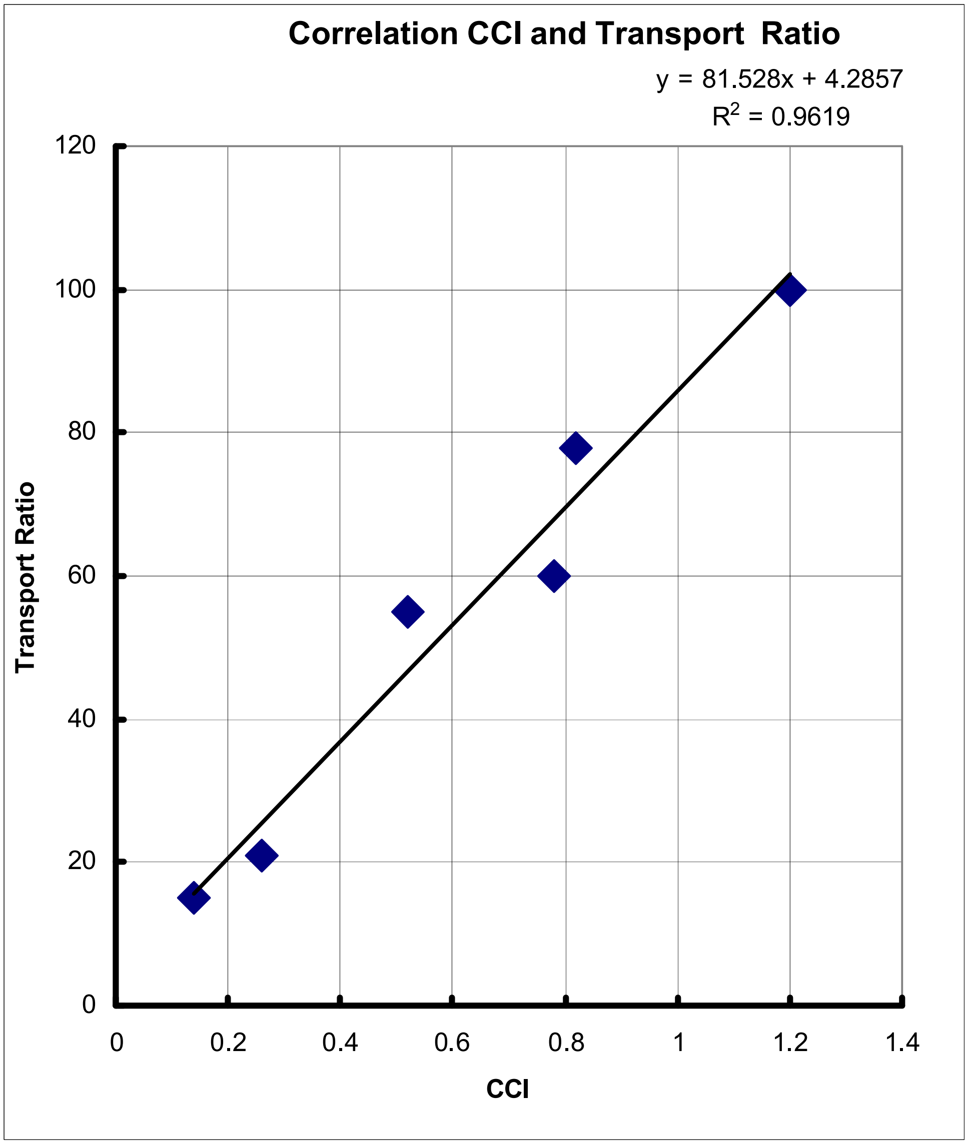

Figure 1
Correlation of Transport Ratio with CCI

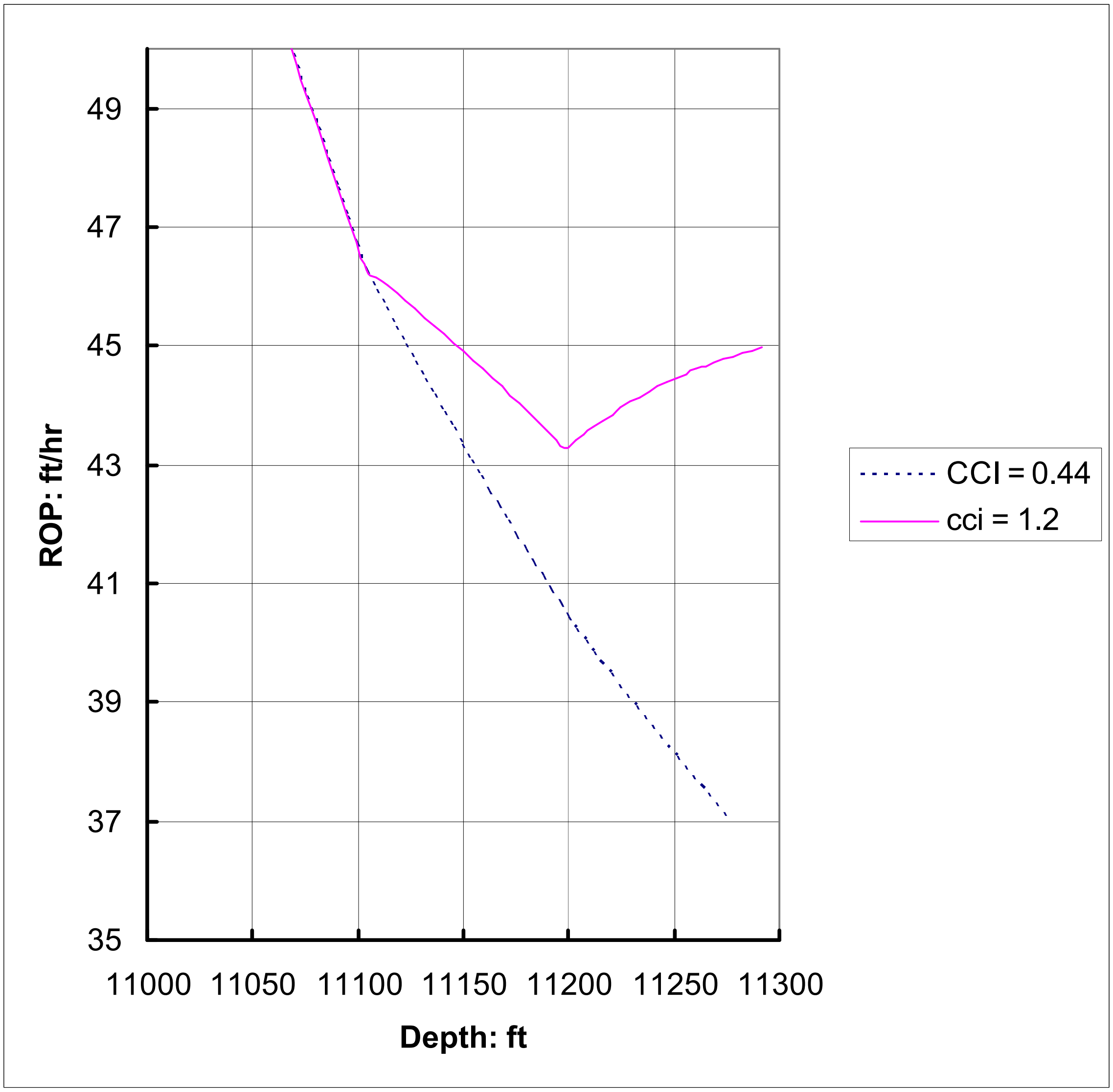

Figure 2
Effect of Carrying Capacity on Drilling Rate

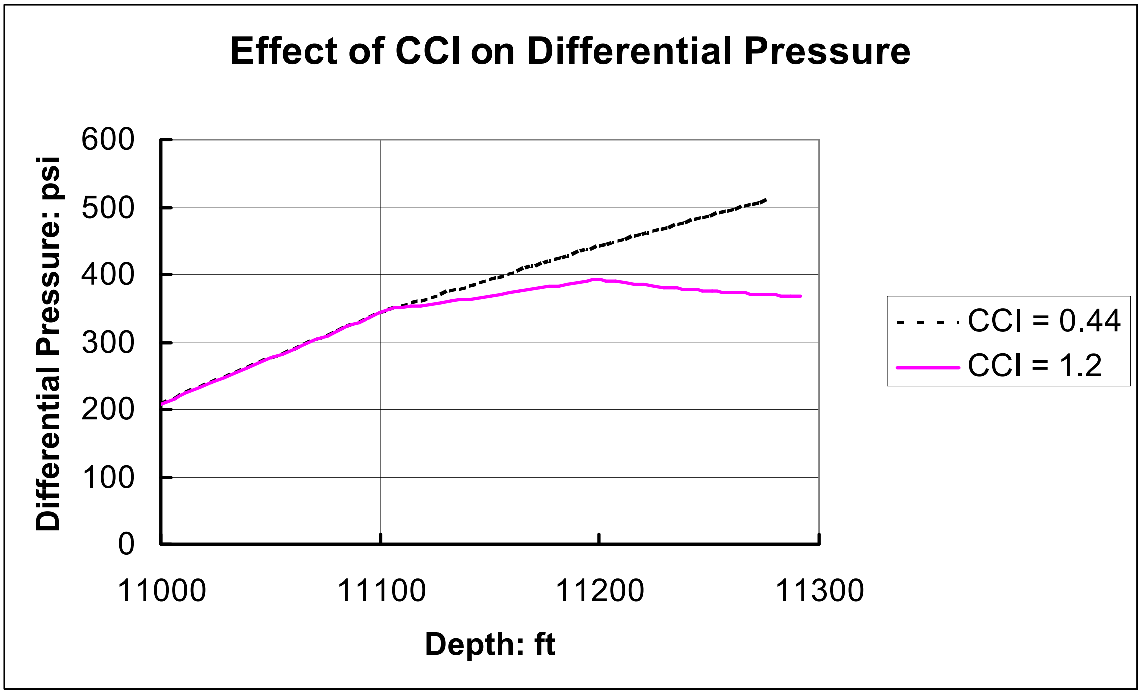

Figure 3
Effect of Hole Cleaning on Differential Pressure