AADE-14-FTCE-14

Application Of Real-Time Solids Monitoring in Well Design, Annulus Pressure Control And Managed Pressure Drilling

Feifei Zhang, Stefan Miska, Mengjiao Yu, Evren Ozbayoglu and Nicholas Takach, University of Tulsa

Abstract

The key to successful drilling through a narrow operating window zone and using MPD operations is to apply proper annular backpressure to get the desired bottom hole pressure. This requires accurate knowledge of the pressure loss in the wellbore. Solids have important effects on annular pressure profile, which must be considered when drilling through a narrow mud window zone and using MPD operations. This paper focuses on the effects of real-time solids monitoring on the wellbore pressure profile. A practical approach is proposed to determine the solids concentration and solids behavior in different positions of the wellbore at any time during drilling, which can give an accurate real-time annular pressure profile in the well.

To study the solids behavior in the wellbore, a series of experiments were conducted on a 90-ft-long, 4.5”×8” full-scale flow loop to simulate field conditions. Solids concentration, bed development and pressure gradient as a function of time were recorded. A solid-liquid moving pattern map including fluid velocity, ROP, inclination angle and fluid properties has been developed for practical applications. Engineering formulas have been proposed to account for the complex solids behaviors in calculating a real-time annular pressure profile in the wellbore.

Results of this work can be used to precisely control the annular pressure profile, guide the setting of annular backpressure in MPD, operation parameter optimization and well path design. Examples of applications of this method are shown in the paper.

Introduction

A narrow operating window is a hazardous scenario for drilling that mostly occurs in deep water drilling and Extended Reach Drilling (ERD). In this scenario, a slight change in bottom hole pressure may lead to formation fracturing, severe drilling fluid loss, or flow influx. During drilling, the annular pressure profile needs to be controlled precisely throughout the wellbore. Solids drilled from the formation have important effects on the pressure gradient and must be considered.

The effects of solids on the annular pressure profile depend on solids fraction, moving patterns of solid-fluid flow, solids density, and the position of the solids in the wellbore. Changes in any of these factors may result in changes in the annular pressure profile that cannot be neglected. Therefore, the solids inside the wellbore need to be monitored carefully during the entire drilling process.

In traditional drilling, bottom hole pressure is at a minimum when the drilling fluid circulation is stopped and only hydrostatic pressure applies to the well. The bottom hole pressure increases after the fluid circulation starts due to friction and solids effects in the annulus. This further decreases the margin for adjusting drilling fluid density to keep the bottom hole pressure within a safe operating window. Minimization of the pressure drop caused by friction and solids is helpful to obtain more flexibility for fluid density and to decrease the amount of casing work. The relation between drilling fluid flow rate and bottom hole pressure is complex. Low fluid flow rate results in low friction loss but high solids fraction in the annulus, while high flow rate results in high friction loss but low solids fraction. Both of these two scenarios generate a relatively large total pressure drop in the annulus.

In the situations of drilling through an extremely narrow operating window zone, the well may be un-drillable because the difference between the bottom hole pressure in static conditions and the bottom hole pressure in flowing conditions exceeds the margin between pore pressure and fracture pressure. Properly and timely monitoring of the solids in the annulus may keep the well from becoming un-drillable.

In managed pressure drilling (MPD), the backpressure needs to be adjusted as the annulus pressure profile changes. After flushing a well, there are little solids left in the annulus. Solids accumulate as drilling continues, which increases the bottom hole pressure. To keep the pressure profile consistent, the backpressure needs to be decreased accordingly. The solids fraction, moving patterns, and solids positions should be monitored in a real-time manner to adjust the backpressure accurately as needed.

This paper provides the tools to predict the real-time pressure profile by monitoring solids in the wellbore. Applications are shown for real-time solids monitoring, drilling through narrow mud window zones, MPD backpressure adjustment, operational parameters optimization and well path design.

Simulation Tool

A solids behavior simulation tool was developed to accurately and monitor solids in the annulus. This tool is based on a massive experimental investigation of solids behavior for different inclined wells and several mechanistic models.

The Low Pressure Ambient Temperature flow loop at University of Tulsa was used in the experimental study. This is a 90-ft-long full-sized flow loop. It has an 8×4.5 in. transparent test section. The solids movement can be observed and recorded through a high-speed camera. The inclination angle of the test section can be changed from 10^o to 90^o from vertical. A photo of the flow loop is shown in Figure 1.

The experimental study was conducted with two kinds of drilling fluids: water and a non-Newtonian fluid. The properties of the non-Newtonian fluid are:

Behavior index n: 0.814

Consistency index K: 0.065 pa·s^m (0.136 lbf· s^m /100ft^2)

Density: 8.34 lbs/gallon (999 kg/m^3)

Solid-Liquid Moving Patterns

Four solid-fluid moving patterns are identified through experimental observation: constant-bed flow, waved-bed flow, packed-dune flow, and dispersed-dune flow. The configurations of these four moving patterns and the moving pattern map are shown in Figure 2. In this moving pattern map, the solid lines represent the transition boundaries for the non-Newtonian fluid and the dashed lines represent the transition boundaries for water. The vertical axis of the moving pattern map is the well inclination angle, and the horizontal axis of the moving pattern map is the solids dispersion number, Dp, which is defined as:

$$Dp = \frac{1000V_{sl}}{(1000V_{ss})^{0.2}} \qquad \text{(Eq-1)}$$

This moving pattern map is valid between 30^o and 90^o angles of inclination. The effect of drill pipe rotation is not considered.

Mechanistic Models

The solid particle behaviors for different moving patterns vary significantly. To predict the solids real-time behavior at any given operational condition during the entire drilling process, mechanistic models are developed for each moving pattern.

Three-layer model

The widely used three-layer model[1] for hole cleaning is suitable for the constant-bed flow. This model was developed to describe cuttings transport in horizontal or highly inclined wells. There are three different regions in the three-layer model geometry: liquid layer, moving bed layer and stationary layer. The formulation of this model contains mass conservation, momentum conservation and closure relationships.

The mass conservation for solid phase and liquid phase can be formulated as Eq-2 and Eq-3, separately:

$$\rho_s A_{sb} C_{sb} U_{sb} + \rho_s A_{mb} C_{mb} U_{mb} = \lambda\, \rho_s A_a U_t \qquad \text{(Eq-2)}$$

$$\rho_L A_{sd} U_{sd} + \rho_L A_{mb}(1 - C_{mb}) U_{mb} + \rho_L A_{sb}(1 - C_{sb}) = \rho_L Q \qquad \text{(Eq-3)}$$

The momentum conservation for liquid layer and the moving bed layer can be formulated as Eq-4 and Eq-5, separately:

$$A_{sd}\left(\frac{DP}{DL}\right) = -\tau_{sd} S_{sd} - \tau_{sdmb} S_{sdmb} - \rho_{sd} g A_{sd} cosI \qquad \text{(Eq-4)}$$

$$A_{mb}\left(\frac{DP}{DL}\right) = -\tau_{mb} S_{mb} + \tau_{sdmb} S_{sdmb} - \frac{F_{mbsb}}{L} - \frac{F_{mb}}{L} - \tau_{mbsb} S_{mbsb} - \rho_{mb} g A_{mb} cosI \qquad \text{(Eq-5)}$$

The stationary bed layer remains stationary in the constant-bed moving pattern. So, this layer needs to satisfy the following relationships:

$$A_{sb}\left(\frac{DP}{DL}\right) + \frac{F_{mbsb}}{L} + \tau_{mbsb} S_{mbsb} < \frac{F_{sb}}{L} + \rho_{sb} g A_{mb} cosI \qquad \text{(Eq-6)}$$

And

$$A_{sb}\left(\frac{DP}{DL}\right) + \frac{F_{mbsb}}{L} + \tau_{mbsb} S_{mbsb} + \frac{F_{sb}}{L} > \rho_{sb} g A_{mb} cosI \qquad \text{(Eq-7)}$$

After simplifications, there are six unknowns in this system: u_l (the mean velocity of the liquid layer), u_{mb} (the velocity of the moving bed layer), C_{mb} (the solid concentration of the moving bed layer), h_{sb} (the height of the stationary bed layer), h_{mb} (the height of the moving bed layer), and $\frac{DP}{DL}$ (the pressure gradient). From the conservation laws for each phase and each layer, four equations are derived to describe the model. Two closure relationships are still required to solve this model. The first closure relationship is the critical fluid velocity to move the solid particles at the surface of the stationary cuttings bed[2]:

$$v_r = \sqrt{\frac{4}{3}\frac{d_s(\rho_s - \rho_L)g}{(C_L \rho_L cos\emptyset + C_D \rho_L sin\emptyset)}} \sin(I + \emptyset) \qquad \text{(Eq-8)}$$

Where, $\emptyset$ is the particle contact angle (30^o in this study), which is shown in Figure 3.

The second closure relationship is the solids dispersion in the moving bed layer[1,3], which can be obtained from the diffusion convection model:

$$\frac{\partial C}{\partial t} = -C\frac{\partial v_s}{\partial y} - v_s\frac{\partial C}{\partial y} + \frac{\partial \Gamma}{\partial y}\frac{\partial C}{\partial y} + \Gamma\frac{\partial^2 C}{\partial y^2} \qquad \text{(Eq-9)}$$

With these two closure relationships, the model can be solved numerically.

Segments model

For waved-bed and packed-dune flow, the segments model can be used to describe solids behavior by simplifying the original configuration, as shown in Figure 4. The simplified geometry contains an upper region, dispersed section and cuttings block section. Similar to the three-layer model, this model contains mass conservation for each phase, momentum conservation for each region and closure relationships.

In the segments model, the solids are assumed to be fully dispersed in the upper region and the dispersed section. The solid particle diameter is assumed to be uniform with a spherical shape. Drill pipe rotation is not considered in the model.

The mass conservation for the solid phase and liquid phase can be formulated as Eq-10 and Eq-11, separately:

$$\rho_s U_u A_u C_u + \rho_s U_d A_d C_d = \lambda\, \rho_s ROP\ A_a \qquad \text{(Eq-10)}$$

$$\rho_L U_u A_u (1 - C_u) + \rho_L U_d A_d (1 - C_d) = \rho_L Q \qquad \text{(Eq-11)}$$

The momentum conservations for the upper region and dispersed section can be formulated as Eq-12 and Eq-13, separately:

$$-A_u \frac{DP}{DL} = \tau_{uw} \cdot S_{uw} + \tau_{ub} \cdot S_{ub} \cdot R_b + \frac{F_{uw}}{L} + \frac{F_{ub}}{L} \cdot R_b + \tau_{ud} \cdot S_{ud} \cdot (1 - R_b) + \rho_u \cdot g \cdot A_u \cdot cosI \qquad \text{(Eq-12)}$$

$$-A_d \frac{DP}{DL} = \tau_{dw} \cdot S_{dw} - \tau_{ud} \cdot S_{ud} + \frac{F_{dw}}{L} + \rho_d \cdot g \cdot A_d \cdot cosI \qquad \text{(Eq-13)}$$

The momentum relations for the solid block region can be expressed as:

$$-A_b \frac{DP}{DL} \le -\tau_{ub} \cdot S_{ub} + \frac{F_{ub}}{L} + \rho_b \cdot g \cdot A_u \cdot cosI \qquad \text{(Eq-14)}$$

And

$$-A_b \frac{DP}{DL} + \tau_{ub} \cdot S_{ub} + \frac{F_{ub}}{L} \ge \rho_b \cdot g \cdot A_u \cdot cosI \qquad \text{(Eq-15)}$$

To solve this model, three closure relationships are required. The first two closure relationships are the critical velocity to move the solid particles and the solids concentration in the dispersed region. These two closure relationships are same as the two closure relationships used in three-layer model, which are shown in Eq-8 and Eq-9.

The additional closure relationship for the segments model is the packed solid block length ratio, R_b, which is the ratio of the cuttings block length and the unit length.

$$R_b = L_B / (L_B + L_D). \qquad \text{(Eq-16)}$$

Through experimental study, it is found that 0.75 is a proper value for R_b.

From the conservation laws, four equations can be obtained for the system. Another two equations are provided by the critical velocity model and the diffusion model. There are six unknowns in this model: DP/DL (the pressure gradient), U_u (the velocity of the upper region), U_d (the velocity of the dispersed region), C_u (the solid concentration of the upper region), C_d (the solid concentration of the dispersed region) and h_u (the height of the upper region). With six equations and six unknowns, the model can be solved numerically.

Dispersed model

For the dispersed-dune moving pattern, the local solids concentration in the wellbore is directly related to the solids slip velocity in the fluid flow. A dispersed model is developed for this moving pattern.

$$C_c = -\left(\frac{v_m - v_s}{2v_s}\right) + \left[\left(\frac{v_m - v_s}{2v_s}\right)^2 + \frac{v_m C_F}{v_s}\right]^{0.5} \qquad \text{(Eq-17)}$$

The solid particle slip velocity at different Reynolds numbers can be obtained from correlations in the literature.[4]

The new mixture flow density is calculated by using Eq 18.

$$\rho_m = \rho_l \cdot (1 - C_c) + \rho_s \cdot C_c \qquad \text{(Eq-18)}$$

The effect of solids on the mixture viscosity is neglected because the solids concentration is very low in dispersed-dune flow.

Real-Time Solids Monitoring

A combination of the models in the previous section is able to predict the solids behavior and pressure profile in the whole well. An integration of these models in a real-wellbore can be used to monitor the real-time solids position, concentration, and moving patterns in the wellbore.

During the drilling process, well parameters and operational parameters change from time to time. Drilling needs to be stopped and other operations need to be run many times before reaching the target. The solids profile in the well may not always be fully developed. Both the cuttings concentration profile and pressure profile are functions of time. At a given position, assume the well is clean before drilling starts, the real-time solids behavior can be monitored using the following steps: 1. divide the well into several parts according to changes of wellbore parameters or drill string parameters; 2. calculate the solids accumulation and the pressure gradient of each part with the given operational conditions; 3. start drilling at t_0 with the given ROP and other operational parameters; 4. calculate the amount of cuttings generated during drilling from t_0 to time t_1; 5. detect the front of the solids in the well starting from the bottom hole by using the calculated solids accumulations at the given operation parameters; 6. calculate the pressure drop in each part of the well; 7. integrate pressure drop to get the pressure profile for the whole well.

The following example shows the application of these models in tracking the solids position for a practical drilling case.

The architecture of the wellbore is shown in Figure 5. This well includes two parts: the cased part and the open hole part.

The kick-off depth of this well is 5045 feet. At the kick-off point, the building rate of the well is 3^o/100 feet until the well inclination angle reaches 60^o. The well inclination angle is kept constant at 60^o for 2000 feet. This part of the well is cemented with 9-5/8 inch casing.

The open hole part of the well is drilled with an 8-½ inch bit at 3^o/100 feet building rate to 90^o, then, maintaining the well inclination angle at 90^o. The final measured depth of the well is 11545 feet.

In this example, the solids behavior is analyzed during drilling the second part of the well. After finished running the 9-5/8 inch casing, the wellbore is clean and there are no solids in the annulus. The operational parameters for drilling the open hole section are shown in Table 1.

Table 1. Operational parameters

Flow rate	500 gpm
ROP	33 ft/hr
RPM	80
Drill pipe	4-1/2"
Fluid density	8.57 lb/gal
K	0.136 lbf· s^m /100ft^2
n	0.814

Figure 6 shows the change of the solids concentration and solids position in the wellbore during the drilling of the open hole section.

In Figure 5 and 6, the critical sliding position is the position where solids start to slide backward upon decreasing the fluid flow rate. For any position in a well, if the inclination angle at that point is smaller than the inclination angle of the critical sliding position, solids will slide downward in the opposite direction of the fluid flow; otherwise, solids do not slide.

At time t=0, the well is clean. After drilling starts, the solids concentration profile starts to develop and the solids front moves toward the wellhead. At about t=10 hours, the solids front reaches the critical sliding position. At about t=17 hours, the solids reach the well head. Thus, within 10 hours, after drilling starts the solids will not slide backward if the flow rate is decreased or stopped. After 10 hours, if the flow rate needs to be decreased or stopped, the solids would slide back and pack in the well. In this case, the sliding solids should be dealt with because they may cause stuck drill pipe and plug the well. If possible, the solids should be flushed out before decreasing or stopping the flow rate. If the solids are packed in the well, drill pipe movement should be minimized since the motion may further compress the packed solids bed. When increasing flow rate, it should be done very slowly. The packed solids may cause a significant pressure surge in the well when the flow rate starts again, which may fracture the formation.

Drilling Through Narrow Mud Window Zone

In some cases, the drilling operating window is extremely narrow. It is difficult to meet the bottom hole pressure requirement only by adjusting the drilling fluid density. The effect of solids on bottom hole pressure may exceed the drilling operating window of the formation.

The following example shows the change in the annular pressure profile during drilling the open hole section of the well in the previous example. The initial and final annular pressure profile is shown in Figure 7. The formation fracture pressure is 4350 psi, and the pore pressure is 3700 psi. It is difficult to keep adjusting the drilling fluid density to meet the requirement of the drilling operating window for this formation. As shown in Figure 7 and 8, the bottom hole pressure would exceed the fracture pressure before reaching the target.

By using a traditional drilling approach, this well is impossible to drill without damaging the formation because of the narrow margin between the pore pressure and the fracture pressure. This un-drillable well can become drillable by monitoring the solids in the annulus properly.

In Figure 8, the bottom hole pressure (BHP) reaches the fracture pressure after drilling continuously for 40 hours (the dashed line). To avoid fracturing the formation, we can stop drilling and flush the solids in the well before the BHP reaches the fracture pressure. The BHP decreases to 3850 psi if cuttings are flushed 30 hours after drilling starts.

The BHP will increase close to the fracture pressure approximately 10 hours after drilling is resumed. Another flushing operation is needed to avoid fracturing the formation. After the second flushing, the well can be drilled continuously for another 20 hours to reach the target.

In this example, drilling through a narrow-window formation can be accomplished by monitoring the solids location and bottom hole pressure in real time.

Back Pressure Adjustment

Another way to drill the well shown in the previous section is to use MPD. The wellbore pressure profile can be controlled precisely by applying backpressure at the outlet of the annulus. In this case, the backpressure needs to be adjusted as the annular pressure drop changes.

For the previous example, assume MPD is used, and the backpressure is 800 psi. The dashed line shows the real-time BHP during drilling without changing the backpressure, which exceeds the fracture pressure at about 40 hours of elapsed time. If the back pressure is decreased by 200 psi at 20 hours (shown in Figure 10), the bottom hole pressure stays within the drilling window.

Application in Drilling Optimization

Another important application for the integrated model is to optimize the drilling operational parameters. In most drilling applications, the pressure drop caused by friction and solids in the annulus needs to be minimized. Pressure drop in the annulus is not always proportional to the flow rate. At low flow rates, the solids concentration in the wellbore is relatively high, which leads to high pressure drop. For these cases, increasing the flow rate can reduce the solids concentration significantly, which actually decreases the total pressure drop. In low solids concentration conditions, the effect of solids on pressure drop is minor. In this case, increasing the flow rate will lead to a significant increase in friction loss, which also increases bottom hole pressure. Thus, there is an optimized flow rate. At the optimized flow rate pressure drop in the annulus is minimized. The following case is an example of flow rate optimization.

The wellbore architecture is the same as the well shown in Figure 5. The well is opened with 26 inch bit and cemented at 1300 feet MD. Then, drilling continues with 17-1/2 inch bit to 5045 feet, which is the kick-off point. At the kick-off point, the well is drilled with a rotary steerable system and a 12-1/4 inch bit. The building rate is 3^{o}/100 feet until the well inclination angle reaches 60 degrees. The well inclination angle is kept constant at 60 degrees and another 2000 feet is drilled. The new drilled part is cemented, and drilling is continued with an 8-3/4 inch bit to the target. In this example, simulations are run for the drilling after casing, and the pressure profile predictions are shown in Figure 11 (a) and Figure 11 (b).

Assume the same operational parameters as shown in Table 1, except the flow rate used in the drilling of the well in this example. Simulations are run for different flow rates to get the minimum pressure drop in the annulus under steady state conditions. In other words, the simulations in this example assume that the flow in the wellbore is fully developed and steady.

As shown in Figure 11 (a), the bottom hole pressure in the flowing condition is significantly larger than the static hydraulic pressure because of friction and the presence of solids. The details of the pressure near the bottom hole region are shown in Figure 11 (b). In this figure, it is evident that the optimized flow rate for this case is about 500 gpm. A lower flow rate leads to high solid concentration in the well, which increases the bottom hole pressure; a higher flow rate leads to more friction loss, which also increases bottom hole pressure.

The solids concentration profile in the wellbore is shown in Figure 12. The solids concentration decreases as the flow rate increases. At 500 gpm, the solids concentration is less than 5% of the concentration in the vertical part of the well, which satisfies traditional hole cleaning requirements. In the inclined and horizontal parts of the wellbore, there is a slight solids deposition, which is acceptable during drilling operations.

Well Design Applications

The solids monitoring tools can also be used in well profile designs. The example in this part shows the application of solids monitoring in choosing the well path. As shown in Figure 13, the requirement of the design is to drill a well from point A to point B. The TVD of point B is 8546 feet and the HD of point B is 3320 feet. Simulations are run for five different well profiles: 3^{o}/100 feet, 6^{o}/100 feet, 9^{o}/100 feet and 15^{o}/100 feet.

The well structures for the four well profiles above are the same: 9-5/8 inch casing part and 8-¾ inch open hole part. The casing TVD is 7700 feet. The drilling operational parameters are shown in Table 2.

Table 2. Operational parameters for well design example

Flow rate	400 gpm
ROP	33 ft/hr
RPM	80
Drill pipe	4 1/2"
Fluid density	8.57 lb/gal
K	0.136 lbf· s^m /100ft^2
n	0.814

The cuttings concentration profiles for different well paths are shown in Figure 14. The length of the build part of the well decreases as the build rates increase. The solids concentration is about 5% in the vertical part of the wells and starts to increase after the kick off point. The solids concentration reaches the maximum when the inclination angles are between 45^{o}~ 55^{o}. There are fewer solids in the building part of the well with low build rate than with high build rate. The building part of the well is the most troublesome part in drilling because of solids deposition and backward sliding. The high build rate well path shortens the intermediate inclined part of the well and decreases the solids accumulation, as shown in the figure.

The pressure profiles for different well paths are shown in Figure 15. The pressure at a given measured depth (MD) is higher for the larger build rate well path. To get to the same target, the MD is shorter for smaller build rate well path.

Figure 14 and 15 show that the effect of build rate on solids concentration and pressure profile is significant from 3^{o}/100 feet to 6^{o}/100 feet. The changes in these two parameters become minor when the build rate is larger than 9^{o}/100 feet. Drag and torque become an issue at very high build rates. In this case, 6~9^{o}/100 feet are the optimized build rates.

Conclusions

In the presented work, solids behavior is analyzed at different operational conditions. Four solid-liquid moving patterns: constant-bed flow, waved-bed flow, packed-dune flow and dispersed-dune flow are identified, and a moving pattern map is developed based on a large amount of experimental data.

Mechanistic models are developed for each moving pattern, and an algorithm is proposed to integrate all the mechanistic models to monitor real-time solids behavior and the annular pressure profile.

Solids monitoring is important in drilling through narrow mud window formations. Proper real-time solids management allows un-drillable wells to become drillable using traditional drilling methods.

Real-time solids and annular pressure profile monitoring are important for adjusting the backpressure in Managed Pressure Drilling.

The pressure drop caused by friction and solids can be minimized by integrating the mechanistic models and running the simulation for the whole wellbore to arrive at an optimized flow rate.

Large build rates reduce solids accumulation in the intermediate part of the well. From the aspect of hole cleaning, build rates should be 6~9^{o}/100 feet since solids accumulation is minor when the build rate is greater than 9^{o}/100 feet.

Nomenclature

A_a = cross section area of the wellbore
A_{mb} = cross section area of the moving bed layer
A_{sb} = cross section area of the stationary bed layer
A_{sd} = cross section area of the dispersed liquid layer
A_u = cross section area of the upper liquid region
A_d = cross section area of the dispersed region in segment model
C = solids concentration
C_C = local solids concentration
C_F = solids concentration at the inlet
C_{sb} = solids concentration of the stationary bed layer
C_{mb} = solids concentration of the moving bed layer
C_u = solids concentration of the upper region
C_d = solids concentration of the dispersed region in segment model
C_L = lift coefficient
C_d = drag coefficient
d_s = solid particle diameter
Dp = solids dispersion number
F_{mb} = friction force between the moving bed layer and wellbore wall
F_{mbsb} = friction force between the moving bed layer and the stationary bed layer
F_{sb} = friction force between the stationary bed layer and wellbore wall
F_{uw} = friction force between the upper region and wellbore wall
F_{ub} = friction force between the upper region and solid block
I = well inclination angle
Q = drilling fluid flow rate
U_{sb} = velocity of the stationary bed, which is 0
U_{sd} = velocity of the dispersed layer
U_u = velocity of the upper liquid layer
U_{mb} = velocity of the moving bed
U_t = drilling speed, which is ROP
v_s = solids particle settling velocity
v_m = solids and liquid mixture velocity
R_b = ratio between solid block region and unit length
S_{sd} = dispersed liquid layer wet parameter
S_{sdmb} = wetted perimeter between liquid layer and moving bed layer
S_{mbsb} = wetted perimeter between moving bed layer and stationary bed layer
S_{ud} = wetted perimeter between the upper region and dispersed region in segment model
S_{ub} = wetted perimeter between the upper region and solid block in segment model
S_{uw} = wetted perimeter between the upper region and wellbore wall
S_{dw} = wetted perimeter between the dispersed region and wellbore wall
ρ_s = solid density
ρ_l = fluid density
ρ_{sd} = dispersed liquid layer density
ρ_{mb} = moving bed layer density
L = wellbore length
τ_{mb} = shear stress between the moving bed layer and wellbore wall
τ_{sd} = shear stress between the dispersed layer and wellbore wall
τ_{sdmb} = shear stress between the dispersed layer and moving bed layer
τ_{mbsb} = shear stress between the moving bed layer and stationary bed layer
τ_{ub} = shear stress between upper region and solid block
τ_{ud} = shear stress between upper region and dispersed region
τ_{uw} = shear stress between upper region and wellbore wall
τ_{dw} = shear stress between dispersed region and wellbore wall
λ = correction factor for the feed cuttings concentration
Γ = diffusion coefficient
$\emptyset$ = particle contact angle

References

1. Doron, P. and Barna, D. and M.Simkhis: "Flow of Solid-Liquid Mixtures in Inclined Pipes", Int. J. Multiphase Flow, Volume 23, Issue 2, p313-323 (1997)
2. R.K.Clark, K.L.Bickham, "A Mechanistic Model for Cuttings Transport", SPE 28306, 69th Annual Technical Conference and Exhibition in New Orleans (1995)
3. R.Ahmed, "Mathematical Modeling and Experimental Investigation of Solids and Cuttings Transport", Norwegian University of Science and Technology (2001)
4. C.A. Shook and M.C. Roco, "Slurry flow: Principles and practice", Butterworth-Heinemann, Stoneham, MA, P16 (1991).

Figure 1. Photo of the experimental facility

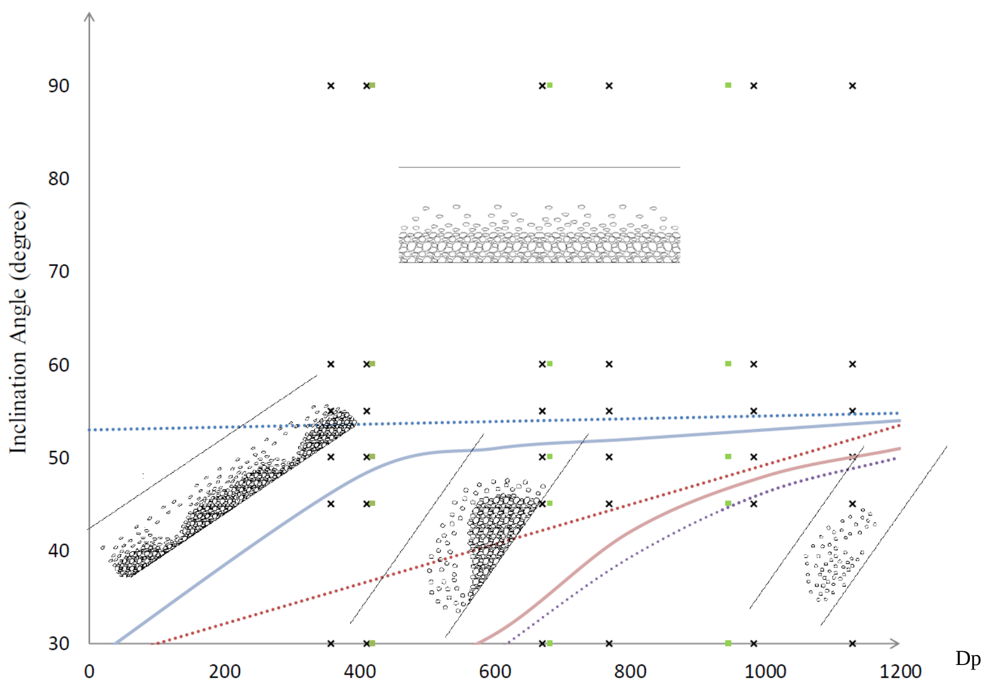

Figure 2. Solid-liquid moving pattern map

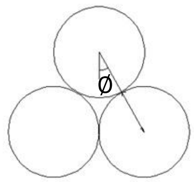

Figure 3. Particle contact angle

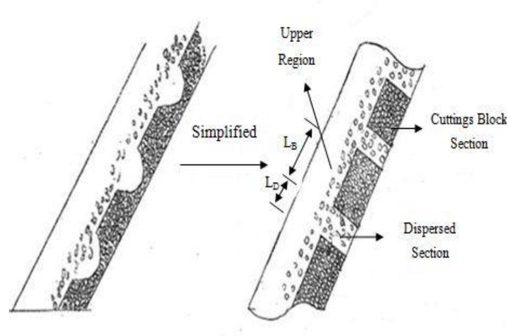

Figure 4. Segment model geometry

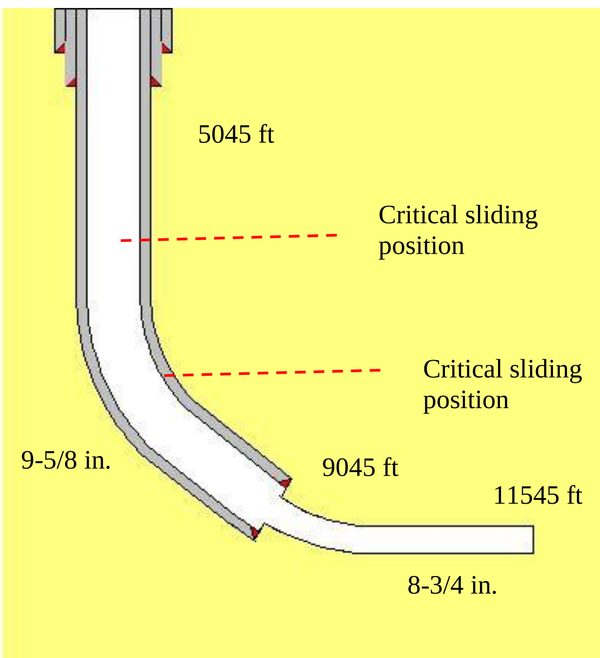

Figure 5. Wellbore architecture

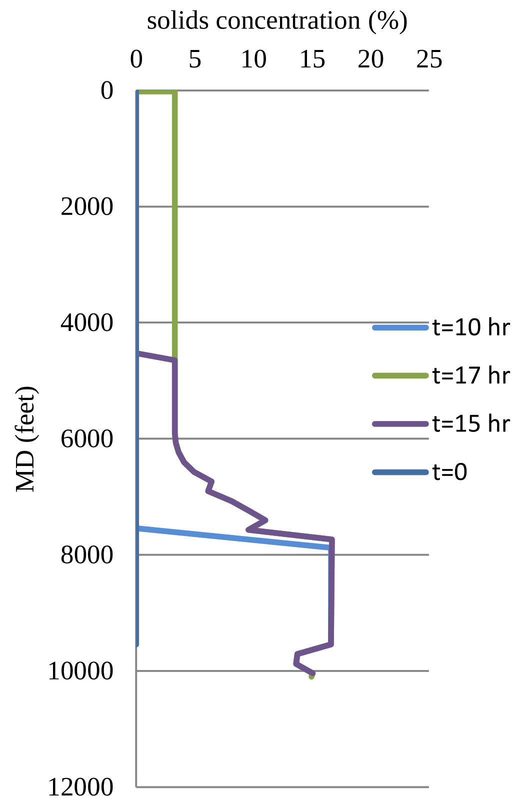

Figure 6. Real-time solids concentration profile in well

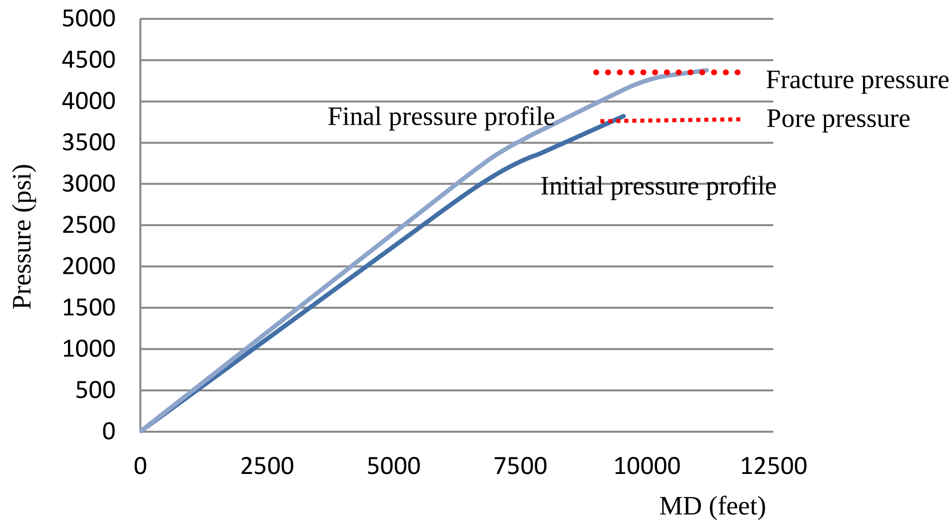

Figure 7. Annular pressure profile

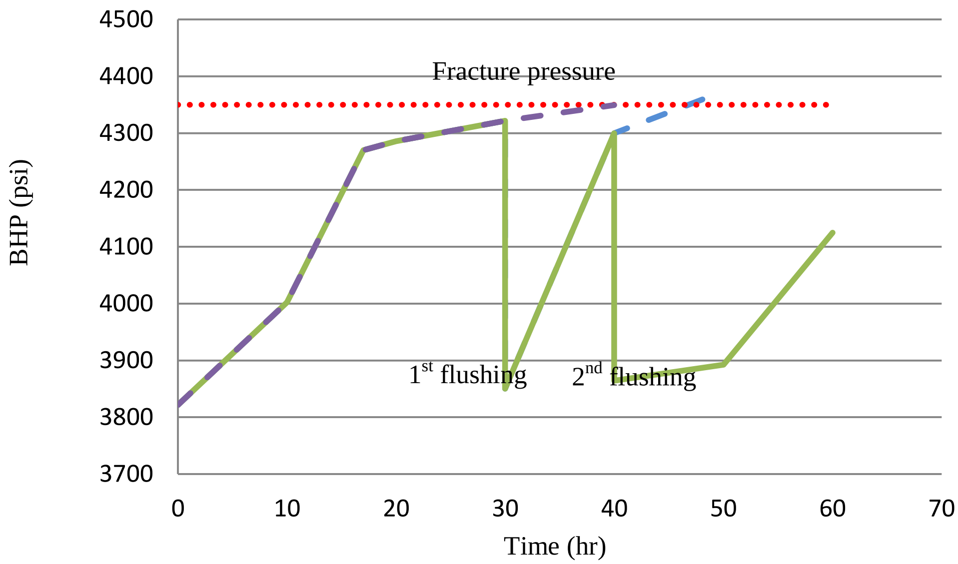

Figure 8. Real-time bottomhole pressure

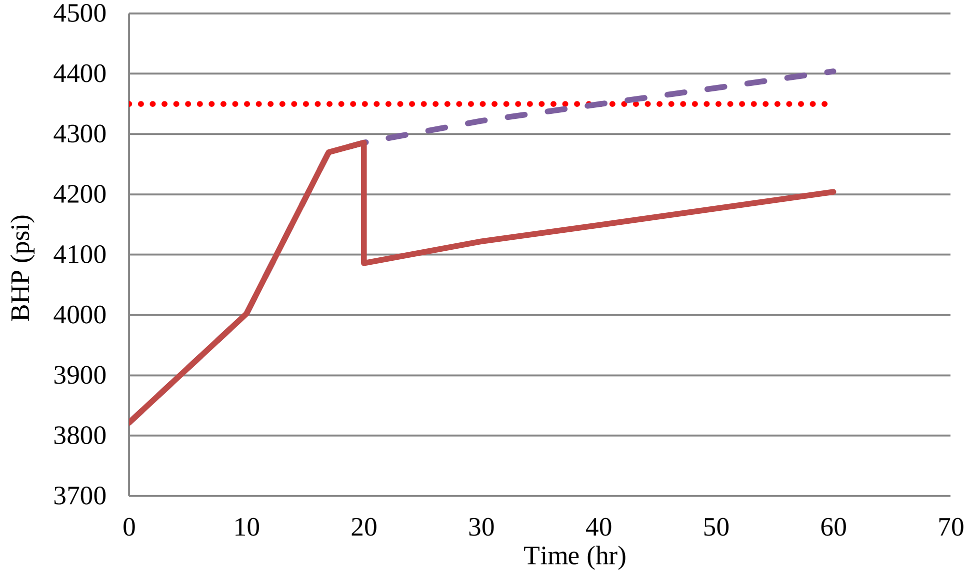

Figure 9. Real-time BHP for MPD

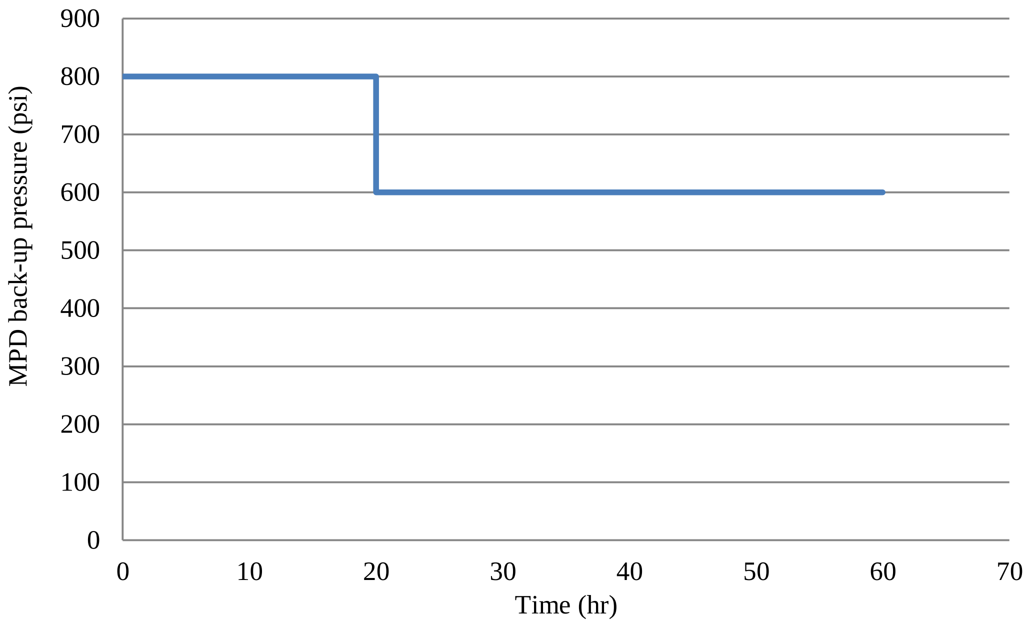

Figure 10. Adjustment of the MPD backpressure

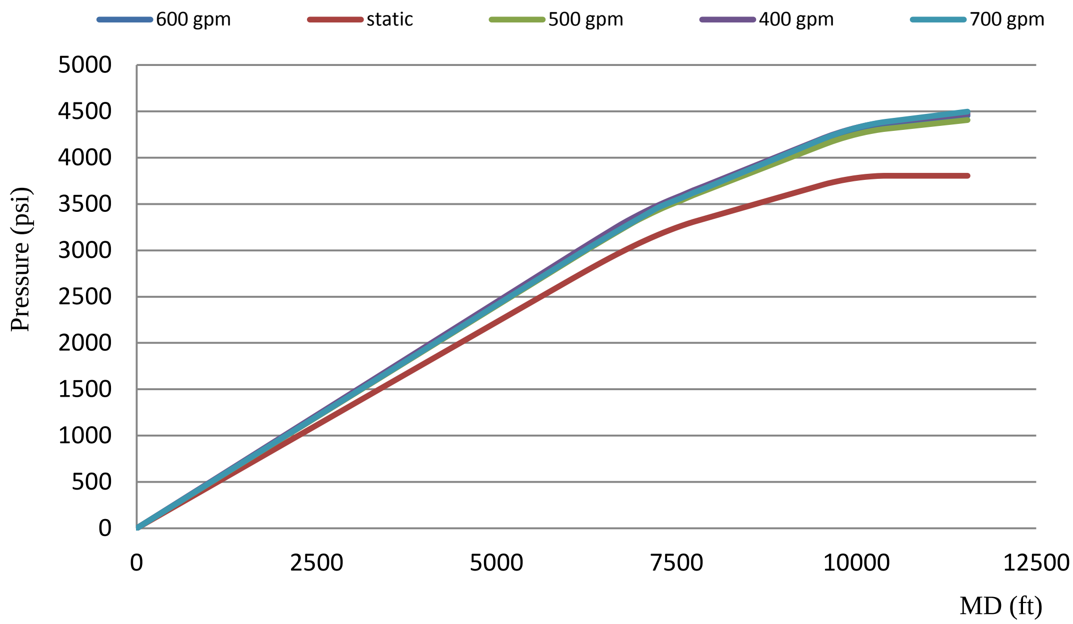

Figure 11(a). Wellbore pressure profile

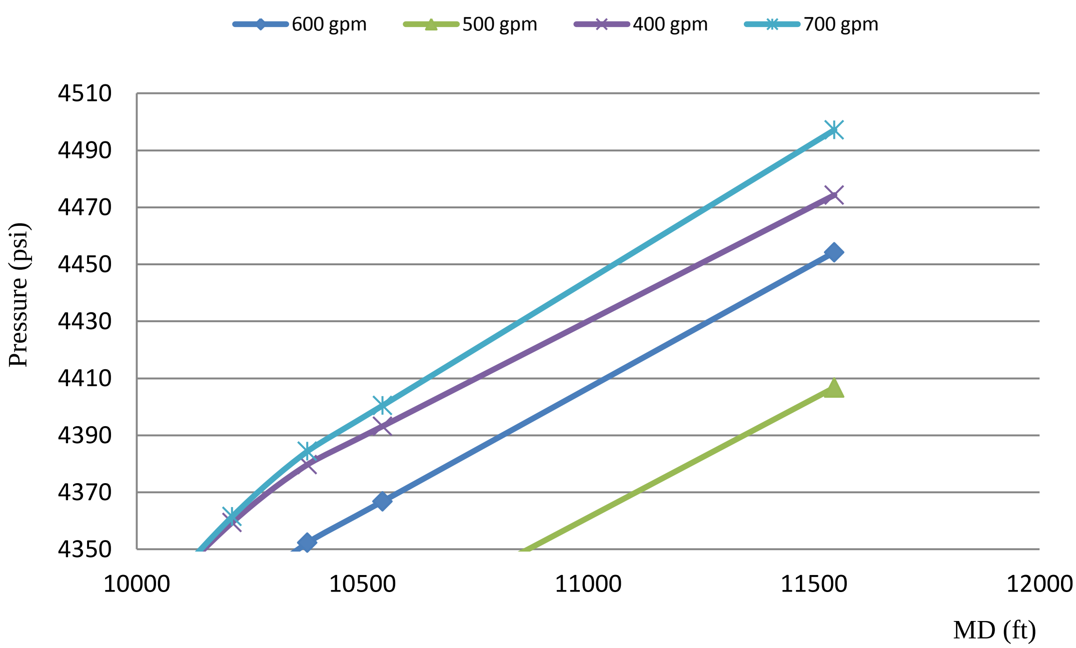

Figure 11(b). Wellbore pressure profile for near-bottom region

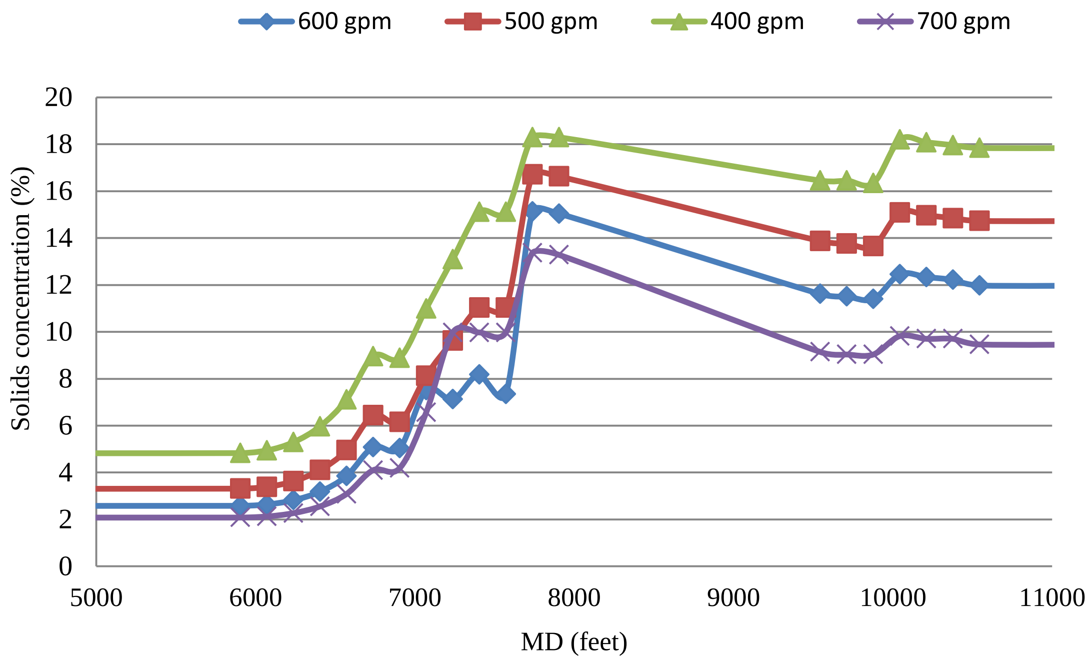

Figure 12. Solids concentration profile in the wellbore

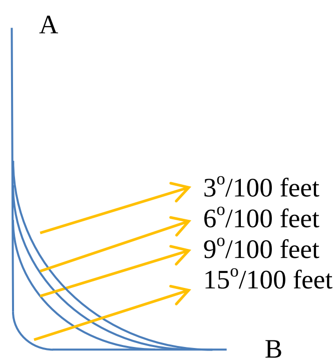

Figure 13. Different well profiles

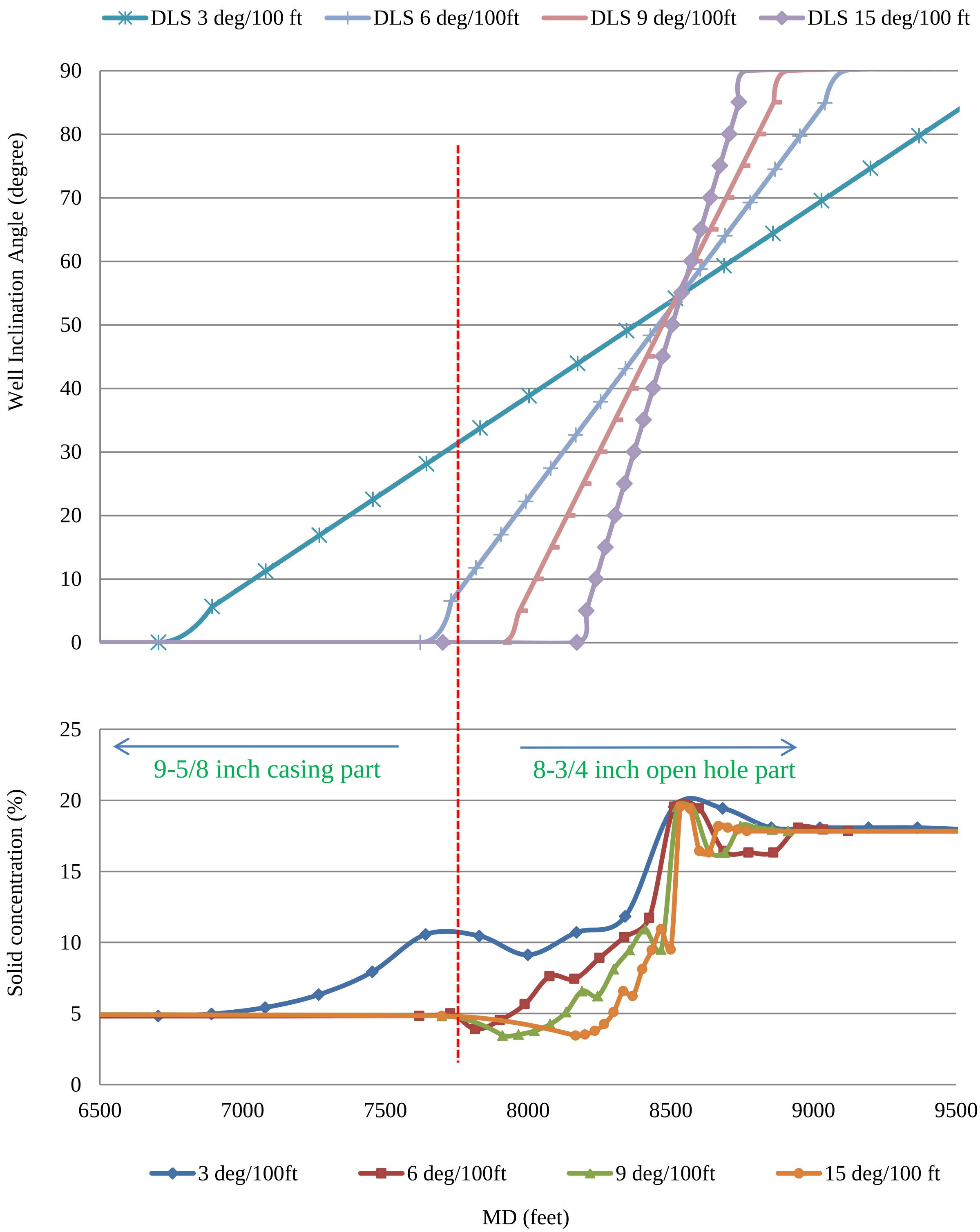

Figure 14. Cuttings concentration profiles in different wellbores

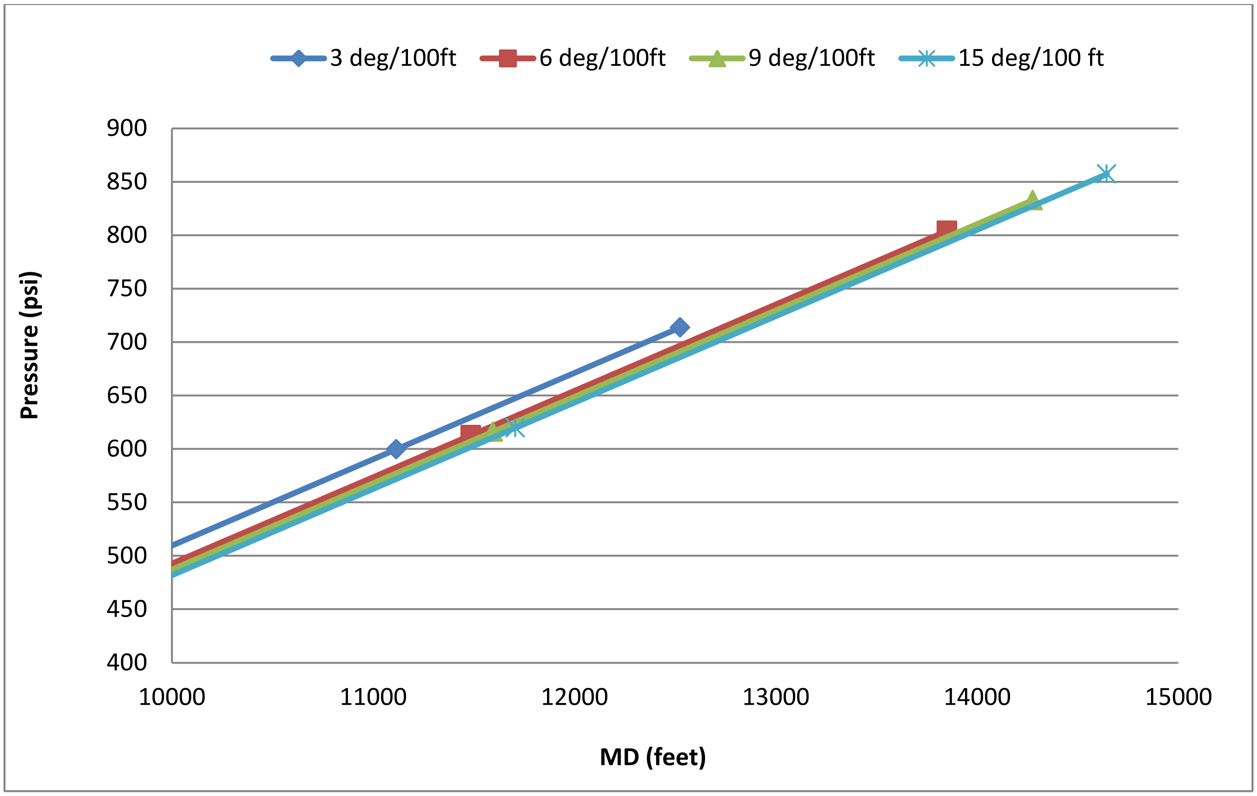

Figure 15. Well pressure minus hydrostatic pressure for different well profiles