Investigation of Lost Circulation and Wellbore Strengthening During Drilling Petroleum Wells: An Overview

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Abstract: Lost circulation is the partial or complete loss of drilling fluid into a formation. It is among the major non-productive time events in drilling operations. Most of the lost circulation events are fracture initiation and propagation problems, occurring when the fluid pressure in a wellbore is high enough to create fractures in a formation. Wellbore strengthening is a common method to prevent or remedy lost circulation problems. Although many successful field applications have been reported, the fundamental mechanisms of wellbore strengthening are still not fully understood. There is still a lack of functional models in the drilling industry that can sufficiently describe fracture behavior in lost circulation events and wellbore strengthening. A finite-element framework was first developed to simulate lost circulation while drilling. Fluid circulation in the well and fracture propagation in the formation were coupled to predict dynamic fluid loss and fracture geometry evolution in lost circulation events. There are two common wellbore strengthening treatments, namely, preventive treatments based on plastering wellbore wall with mudcake before fractures occur and remedial treatments based on bridging/plugging lost circulation fractures. Two analytical models were developed for the investigation of preventive and remedial wellbore strengthening. The models developed and analyses conducted in this paper present a useful step towards the understanding of the fundamentals of lost circulation and wellbore strengthening, and provide improved guidance for lost circulation prevention and remediation.

1. Introduction
Lost circulation is the partial or whole losses of drilling fluid into the formation during drilling. It is a major cause of non-productive time (NPT) in the drilling industry\cite{1}. Lost circulation can lead to various drilling incidents, such as differential sticking and well control events, which further increase NPT and drilling costs\cite{2}. Most lost circulation events are due to fracture extension from the wellbore to the far-field region. Therefore, it is a fracture initiation and propagation problem, occurring when the BHP is high enough to create fractures into the formation. Lost circulation commonly happens in formations with narrow drilling mud weight windows. Several typical scenarios having a narrow drilling mud weight window include depleted zones, deep-water formations, naturally fractured formations and deviated wellbores\cite{3-4}.

![Figure 1. Lost circulation (www.airdrilling.com).](image).

To drill through problematic zones with a high risk of lost circulation, drilling engineers use some approaches to artificially increase the fracture pressure (maximum pressure a wellbore can sustain without significant fluid loss) and hence widen the drilling mud weight window by bridging, plugging, or sealing the fractures. These approaches are called “Wellbore Strengthening”. Currently, there are mainly two types of wellbore strengthening methods in the drilling industry. They are hoop stress enhancement method, e.g. Stress Cage\cite{5} and Fracture Closure Stress\cite{6}, and fracture resistance enhancement method, e.g. Fracture Propagation Resistance\cite{7} and Tip Screen-out\cite{8-9}.

Although a few successful applications of wellbore strengthening have been reported, there is still a lack of a clear understanding of its fundamentals and a lot of disagreements still exist. Therefore, a compressive investigation of fracture behaviors during lost circulation and wellbore strengthening is necessary and crucial for understanding their fundamentals and designing proper wellbore strengthening treatments.

2. Mud weight window
Drilling mud weight window is defined as the margin between the maximum mud weight before the occurrence of lost circulation and the minimum mud weight to balance formation pore pressures or avoid excessive wellbore failure. Lost circulation events commonly occur in formations with narrow drilling mud weight windows.
For example, Figure 2 shows schematically the mud weight window in a depleted formation. The reduction of pore pressure in the depleted zone results in a reduction in fracture gradient. However, the bounding and inter-bedded shale layers will maintain their original pore pressure and fracture gradient. Therefore, it may be difficult to reduce the drilling fluid density sufficiently to maintain equivalent circulating densities (ECD) below the depleted zone fracture gradient. Figure 3 shows schematically the mud weight window in a deepwater formation. Compared with wells drilled onshore or in a shallow water formation, the deepwater well has a much narrower mud weight window. Thus, it very easy for wellbore pressure to overcome the fracture pressure and induce lost circulation event.

3. Modeling Lost Circulation
Lost circulation while drilling is simulated using a coupled fluid flow and mechanics numerical model in this study based on the finite-element method. A lost circulation system generally consists of three components: the well, the fracture, and the formation as shown in Figure 4. In lost circulation simulation, drilling mud circulation in the wellbore, fracture growth and fluid flow in the fracture, formation rock deformation and pore fluid flow should be modeled simultaneously, as shown in Figure 5.

Figure 2. Mud weight window in a depleted formation[4].

Figure 3. Mud weight window in a deepwater formation.
Figure 4. Schematic of a lost circulation system with the wellbore, fracture, and formation\cite{10}.

Figure 5. The coupling between wellbore, fracture, and formation.

A 2D finite element lost circulation model is developed as shown in Figure 6. The formation is in a plane strain condition. The well is vertical. The yellow vertical line is the drilling pipe, drilling mud is injected into the pipe. The blue vertical line is the annulus, fluid flows back from the annulus. The drilling pipe and annulus are connected at the bottom hole, and they are tied to the wellbore wall to enforce the fluid conservation and stress equilibrium between the wellbore and formation. A pre-defined fracture path (the fracture will extend along this path) is assigned along the direction of the maximum horizontal stress $S_{\text{hmax}}$. Using this model, we can simulate static fluid loss and dynamic fluid loss. Here static loss means fluid loss without mud circulation in the wellbore, for a certain formation, the static loss is only controlled by the gravity pressure in the wellbore which only depends on the density of mud. Dynamic loss means fluid loss with mud circulation, dynamic loss is also affected viscous pressure, which is also influenced by mud viscosity, pump rate, and annulus clearance.
Figure 6. Lost circulation model[10].

The model can be used to get several outputs we are interested in lost circulation study, including fluid loss rate, returned circulation rate, bottom hole pressure, and fracture growth/geometry while circulating drilling fluid, as shown in Figures. 7 and 8. From these figures, we can see, as expected, when fluid loss increases, the returned circulation rate will decrease.

Figure 7. The simulation results of fluid loss rate, returned circulation rate, and bottom hole pressure (BHP).

Figure 8. The simulated lost circulation profile.

4. Modeling study of wellbore strengthening
4.1 Preventive wellbore strengthening

Preventive wellbore strengthening treatment is to add additives, such as lost circulation materials, to drilling mud to build a layer of low-permeability mudcake on the wellbore wall which can inhibit fracture creation and increase the sustainable pressure of the wellbore. Mudcake buildup on the wellbore wall plays an important role in preventing lost circulation. However, the time-dependent mudcake buildup and properties have been plaguing the drilling industry for years. An analytical model is first derived to quantify the effects of mudcake thickness, permeability, and strength on wellbore stresses and fracture pressure, as shown in Figure 9. Steady-state fluid flow is assumed for the analytical model, so it does not consider the time-dependent effects.

![Figure 9. Schematic of the mudcake model](image)

We are interested in getting wellbore stress for this problem. Several components contribute to wellbore stress, including in-situ stress, wellbore pressure, varying pressure around wellbore induced by fluid flow from the wellbore to the formation, and strength of the mudcake. Adding the stress induced by these components, we can get the total stress around the wellbore. After that, the effective stress can be determined which is equal to total stress minus pore pressure. Finally, using a tensile failure criterion, the fracture pressure can be determined for a wellbore with a layer of mudcake (Eq. 1).

$$P_f = \frac{3\sigma_n - \sigma_H + \left[2\eta(M-N) - B\right]P_e + \frac{2Y}{\sqrt{3}} \ln \frac{R_o}{R_i}}{2 + 2\eta(M-N) - B}$$  \hspace{1cm} (1)

where $P_f$ is fracture pressure; $\sigma_n$ and $\sigma_H$ are the minimum and maximum horizontal stress, respectively; $\eta$ is the poroelastic stress coefficient; $P_e$ is the far-field pore pressure; $Y$ is the yield strength of the mudcake; $R_o$ and $R_i$ are the outer and inner radius of the mudcake. $M$, $N$, and $B$ are factors related to the geometry and permeability of the mudcake\(^{[11]}\).

This solution takes into account the effects of mudcake permeability, thickness, and strength on the fracture pressure of a wellbore plastered by a layer of mudcake. Using the static mudcake model, we analyzed the effect of mudcake thickness, permeability, and strength on wellbore fracture pressure in their typical ranges. It can be observed that the mudcake strength in its typical range has a negligibly small effect on wellbore stress (Figure...
10a). However, mudcake thickness and permeability affect the fracture pressure greatly. The larger the thickness or the smaller the permeability, the higher the fracture pressure or the “strength” of the wellbore (Figures 10b and 10c). Refer to [12-14] for the characterize of mudcake properties.

Figure 10. The effect of mudcake strength, mudcake thickness, and mudcake permeability on fracture pressure.

4.2 Remedial wellbore strengthening

Remedial wellbore strengthening methods attempt to “strengthen” the wellbore after fractures have already occurred on the wellbore. It is an effective method to mitigate or stop fluid loss by bridging the fractures with lost circulation materials (LCMs). The ultimate objective of remedial wellbore strengthening treatments is to increase the fracture pressure that a wellbore can sustain without significant fluid loss and widen the drilling mud weight window.

Figure 11 is a schematic of an analytical remedial wellbore strengthening model. The fracture is bridged inside with a plug. We are interested in how much pressure a wellbore can withstand after bridging the fractures as shown in this figure. We consider the problem is in a plane strain condition. Rock is linear elastic. The bridge is a perfect bridge, which means it completely separates the fluid ahead and behind it. There are two symmetric, short fractures in the direction of Shmax. The advantage of the analytical model it can give a direct prediction of fracture pressure, and due to its fast feature, it has the potential for a real-time application while drilling.
Figure 11. Schematic of the analytical remedial wellbore strengthening model.

The problem can be solved using linear elastic fracture mechanics theory and superposition principle. Fracture pressure solution after bridging the fracture is shown in Eq. 2. From the equation, we can see that fracture pressure \( P_f \) is affected by in-situ stress \( (S_{H_{\text{max}}} \text{ and } S_{H_{\text{min}}}) \), pore pressure \( (P_p) \), the geometry of the wellbore-fracture system \( (F_1 \text{ to } F_4 \text{ are the geometry factors}), \) and the fracture toughness \( (K_{IC}) \).

\[
P_f = \frac{1}{2} \frac{1}{F_1 + F_2 - F_4} K_{IC} + \frac{1}{2} \frac{F_1 + F_2}{F_1 + F_2 - F_4}, \quad (S_{H_{\text{max}}} + S_{H_{\text{min}}}) - \frac{1}{2} \frac{F_1 + 3F_2}{F_1 + F_2 - F_4}, \quad (S_{H_{\text{max}}} - S_{H_{\text{min}}}) - \frac{F_4}{F_1 + F_2 - F_4} \cdot P_p
\]

Figure 12. The effect of horizontal stress ratio, pore pressure, and bridge location on fracture pressure\(^{[15]}\).

Figure 15a shows fracture pressure for various horizontal stress ratios \( (SH/Sh) \) and bridge location. We can see the higher the stress ratio, the lower the fracture pressure. Figure 15b shows the effect of pore pressure on fracture pressure. At the same bridge location, the smaller the pore pressure, the larger the fracture pressure we can get after bridging. This means remedial wellbore strengthening treatment should be more effective in a depleted reservoir than in a deepwater high-pressure formation because the pore pressure is low in depleted reservoirs.

5. Conclusions
This paper introduces a finite-element framework to simulate lost circulation during drilling with the circulation of drilling fluid. Circulation of drilling fluid in the wellbore and fracture propagation in the porous formation are coupled together to predict the dynamic fluid loss and fracture geometry evolution in the drilling process. The numerical model provides a unique new way to model lost circulation in drilling. An analytical solution is introduced to investigate the role of mudcake on preventive wellbore strengthening treatments based on plastering wellbore with mudcake. The analytical solution derived based on steady-state fluid flow assumption incorporates the effects of mudcake thickness, permeability, and strength on wellbore stress and fracture pressure. An analytical solution is introduced for remedial wellbore strengthening treatment based on plugging/bridging lost circulation fractures using lost circulation materials. The analytical model, based on linear elastic fracture mechanics theory, provides a fast procedure to predict fracture pressure change before and after fracture bridging.

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