



Integrating Optimization of Drilling Parameters with Wellbore Stability

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Abstract

The drilling of wells in deepwater and extended reach environments is characterized by staying within the window between the formation pore pressure and fracture gradient. The success of such wells having complex geometry or a high degree of difficulty hinges on maintaining wellbore stability (WBS) and optimization of drilling parameters. However, during the pre-well planning phase, geomechanical wellbore stability modeling generally focuses only on predicting the required surface fluid density. On the other hand, "optimized" drilling parameters are identified by modeling pressure drops, hole cleaning and rate of penetration without any consideration of wellbore geomechanics.

In this paper, wellbore hydraulics and geomechanical wellbore stability are integrated to assess the volume of rock that is subjected to shear failure due to annular pressure fluctuations during the wellbore construction process. Conversely, the effect of the failed rock on equivalent circulating densities (ECDs) and pump requirements for hole cleaning are also estimated.

This comprehensive approach to modeling WBS during the wellbore construction process also accounts for:

- ECD, Swab and Surge Pressures
- Fluid density fluctuations due to OBM/SBM compressibility and thermal expansion
- Change in near-wellbore formation pressure due to water influx into shales driven by higher hydraulic gradients during drilling
- Chemo-mechanical effects on wellbore stability

The improved understanding of wellbore instability events is documented using data from an extended reach well in the North Sea. Such an integrated approach to combining hole cleaning / hydraulics and geomechanical wellbore stability approaches real-time optimization of the drilling process and can help the drilling industry avoid unwanted surprises that can lead to unstable wellbores.

Introduction

The effects of drilling operations on wellbore stability was recently re-evaluated for an extended-reach drilling (ERD) well in the North Sea.⁶ Specifically, changes in pump rate, drill string rotation speed, and ROP were made to determine their relative effects on the stability of a section near the bottom of the 12.25-in. interval located in a problematic shale zone at 12381 ft TVD. Wellpath optimization, calculation of safe mudwindows and subsequent hydraulics optimization had been carried out in an earlier work.^{1,2}

In this paper, the volume of rock subjected to failure due to annular pressure fluctuations during various phases in the well construction process is estimated. Next, the effect of the failed rock on ECDs and hole cleaning are estimated. It must be noted herein that a chemoporoelastic model accounting for chemical interaction between the drilling fluid and the formation, as well as full coupling between the change in pore pressure and effective stresses has been used.^{3,4,5,6} Key areas addressed in this study include:

- Surge/swab effects on time-dependent wellbore stability and the effect of the volume of failed rock on ECDs and hole cleaning
- The potential for localized circumferential tensile failure with cessation of mud circulation and ECD effects and the effect of the failed region on cuttings load

With this iterative approach to combining hole cleaning/hydraulics/wellbore stability studies, the pre-well planning process on future wells can be further integrated to help ensure project success. Indeed, such an effort approaches real-time optimization of the drilling process that can more quickly identify potential incidents of shale instability and/or lost circulation.

Drilling Near 12.25-Interval TD

The drilling fluid density near interval TD was reported to be 12.0 lbm/gal measured at surface, with an ECD of 12.35-12.40 lbm/gal as measured by pressure-while-drilling (PWD) tools. Once casing point was reached, the hole was circulated clean but tight spots

were encountered while tripping out of the hole. Seeing that the shale zones were unstable over a period of several days, the operator, upon running back to bottom, decided to raise the system surface density to 12.5 lbm/gal, a level slightly over the ECD that the wellbore had experienced while drilling and circulating.

Also noteworthy during this time is the difference between the density as measured at surface and the predicted static density on bottom. When the effects of temperature and pressure are taken into account on the LTOBM density (in this case thermal expansion masking compressibility effects), the net result is that the fluid static downhole density was 0.13 lbm/gal lighter than that measured at surface.⁶ Hence the LTOBM density on bottom during the hole cleaning trip out was slightly less than 11.9 lbm/gal.

Determination of Safe Operating Window

Using the conditions before running casing and a drilling fluid surface density of 12.5 lbm/gal, the window for safe drilling between formation collapse and formation fracture initiation was determined.⁶ The pertinent input parameters used in the modeling were taken from the earlier study; the activity of the aqueous phase of the LTOBM was also input so the chemoporoelastic model could be used. At a 63° angle, the modeled drilling fluid density was predicted to be 12.7 lbm/gal, a level slightly higher than the final density used while running casing. With the hole giving some problems on the cleaning trip out, a density at interval TD of 12.0 lbm/gal was clearly inadequate, and densities of 12.35-12.4 lbm/gal could be considered “borderline” at best. In **Fig. 1** the various mud densities and ECD values are detailed for the modeled case.

Holes drilled in the direction of the maximum horizontal stress require higher mud weights to prevent hole collapse compared to holes drilled in the direction of the minimum horizontal stress.⁶ For deviations greater than 75° from the vertical, hole collapse is imminent if the wellbore is oriented along the maximum horizontal stress. For hole angles greater than 75°, the high static mud weights required to prevent hole collapse may serve to increase mud pressure penetration into the weak shale laminations and thereby hasten wellbore instability.²

Breakout Orientation and Hydraulic Modeling

The impact of hole enlargement resulting from breakout on hole cleaning is effected by the orientation of the breakout. Generally, for vertical wells, breakouts occur along the direction of the minimum horizontal stress and their position can be easily identified for hydraulic modeling purposes. For near-horizontal wells, any hole collapse on the top side of the hole will fall directly into the annulus, contributing to cuttings loading therein. In severe cases, hole pack-off and stuck pipe can result. For breakouts that occur in the low side of

the hole on the vertical axis, the effects of gravity serve to initially keep the cuttings in place. Some may be removed through circulation and drill pipe rotation, but the removed volume is soon replaced by drilled cuttings. The overall effect is much like that of washouts. The effects of such breakouts can be modeled hydraulically using enlargements for one side only.

For other orientations of breakouts, which are more the norm compared to that discussed above, the hydraulic effects should be modeled using calculated enlargements for both sides.

Swab Effects

The effects of swab pressures lower effective pressures on the wellbore wall and wellbore instability can result from the pressure reduction. Here, the effects of swab on wellbore stability have been analyzed for a variety of drillpipe pulling speeds. Using hydraulics modeling, the equivalent swab pressure was estimated to be 0.3 – 0.35 lbm/gal for pipe pulling speeds ranging between 30 and 90 ft/min (**Fig. 2**). The effect of this swab on wellbore stability was analyzed using a chemoporoelastic model⁶. **Fig. 3** shows the predicted collapse after the wellbore is subjected to swab conditions for an interval of 2 hours. Here, wellbore failure principally along one axis is predicted, with breakouts of about 2-in. maximum. The volume of failed rock generated for a 30-ft hole section is 4.93 ft³, giving an increase of 20.1% in rock volume to be cleaned over that of gauge hole.

When breakouts occur, their effects on hole cleaning are negative. Not only do more particles fall into the annulus, but they can be of much-larger sizes than those normally cut by the drilling bit, and their slip velocities can be quite high. Moreover, the resulting enlargement serves to increase annular area exposed to flow and fluid velocities in the annulus fall accordingly. These doubly-negative effects of breakouts on hole cleaning are modeled in **Fig. 4**. Here the predicted transport efficiencies for breakout particles for a variety of diameters are given for 3 cases:

- The base case where no breakout has occurred
- The case of vertical breakout
- The case of non-vertical breakouts

Here the decreasing efficiency in cuttings transport is shown, with the larger-diameter particles for non-vertical breakouts representing the worst case.

Radial Stress Variations

In standard drilling practice, the static drilling fluid density is generally greater than pore pressure. However, when drilling through a low-permeability formation (eg. shales), the near-wellbore pore pressures approach over time the ECD as the drilling fluid is circulated. This is due to the low efficiency of the barrier (filter cake, pore plugging with specially-selected solid

materials, etc.) formed at the borehole wall. Once circulation is stopped (as when making connections, tripping out, etc.), the wellbore pressure now equals the static mud weight and is lower than the near-wellbore pore pressure. These changes in pressure at the wellbore wall generate tensile radial stresses and circumferential tensile failure. In **Fig. 5 and 6**, the results are shown of a modeled case in which 100% transmission of circulating pressure occurs. After drilling with an ECD (calculated at an ROP of 100 ft/hr, a drill pipe rotation speed of 100 rev/min, and a surface drilling fluid density of 12.1 lbm/gal), circulation is stopped. Here, the effective radial stress is predicted to be tensile for approximately 2 hr generating **6.87 ft³** of failed rock over a 30 ft hole section (i.e., 28% of additional rock volume is generated).

The effects of this volume of failed rock are shown in **Fig. 7**. As in the swab case discussed earlier, the effects on cuttings transport are negative. With the increased volume of breakout in this case, the predicted results are more negative than for the swab case. Less negative effects of circumferential tensile failure can be expected when transmission of circulating pressure on the wellbore wall is reduced.

Conclusions

A number of conclusions can be drawn from the material presented in this study:

- The integration of hydraulic modeling and wellbore stability modeling can provide increased understanding of drilling events and field problems.
- Given the activity of the aqueous phase of an invert emulsion drilling fluid, the chemoporoeleastic wellbore stability model can be used to better understand fluid and rock interactions.
- A more refined safe operating window between formation collapse and fracture initiation can be determined through the integrated modeling approach used in this paper.
- The hydraulic effects of surge and swab can be modeled in terms of wellbore stability, and the results can be graphically presented for increased understanding.
- Rapid or frequent changes in wellbore pressures at the wellbore wall can have an effect on the effective radial stress, and these changes can lead to circumferential tensile failure.

Nomenclature

TD = total depth

TVD = true vertical depth

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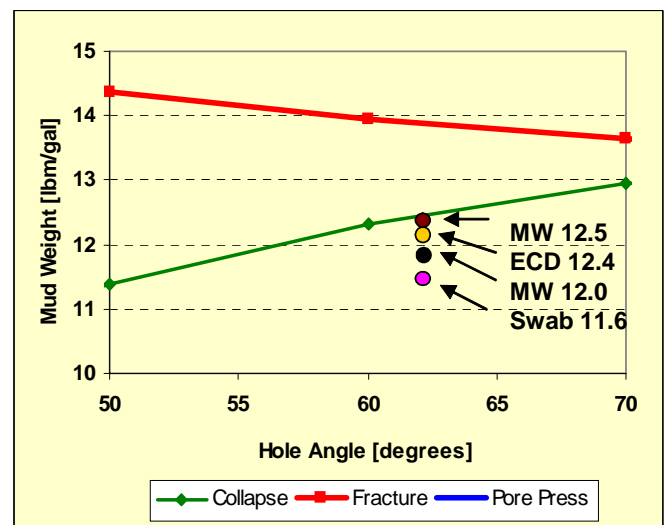
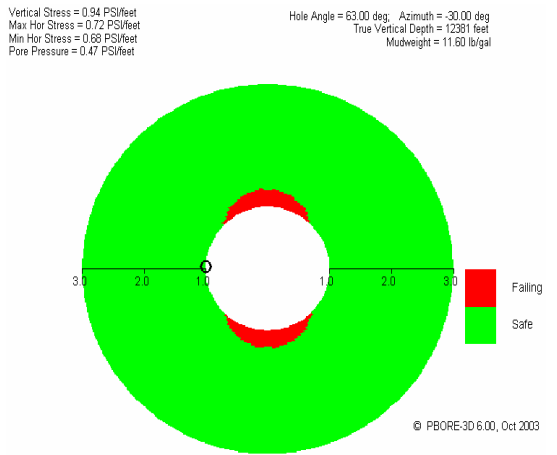
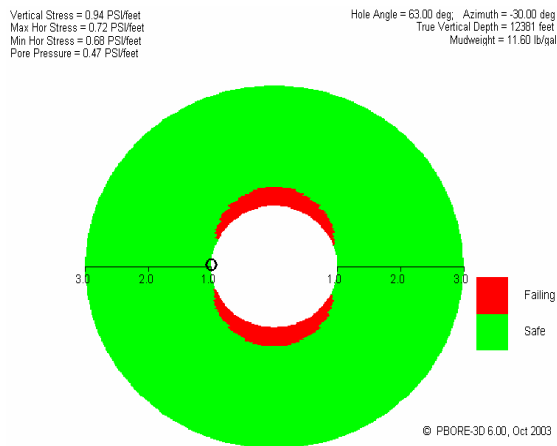


Fig. 1 - Drilling fluid densities, ECD, and swab at 63° deviation (12.25-in. interval at TVD = 12,381 ft., mud activity = 0.77).



(3a)



(3b)

Fig. 3 - Progressive collapse failure of the wellbore from 2 hr. (a) to 24-hr. (b) with ECD = 11.6 lbm/gal.

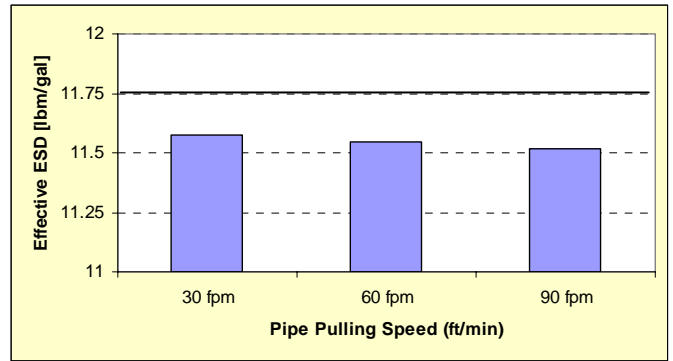


Fig. 2 – Predicted bottomhole static drilling fluid densities resulting from swab events at 3 pipe pulling speeds.

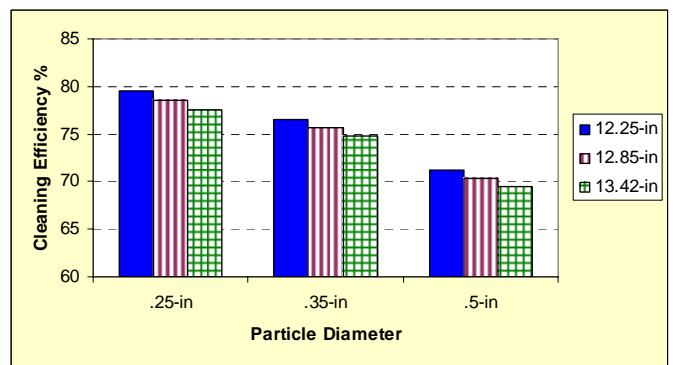


Figure 4 – Predicted particle cleaning efficiencies by particle size for 3 average hole sizes resulting from breakouts due to swab effects.

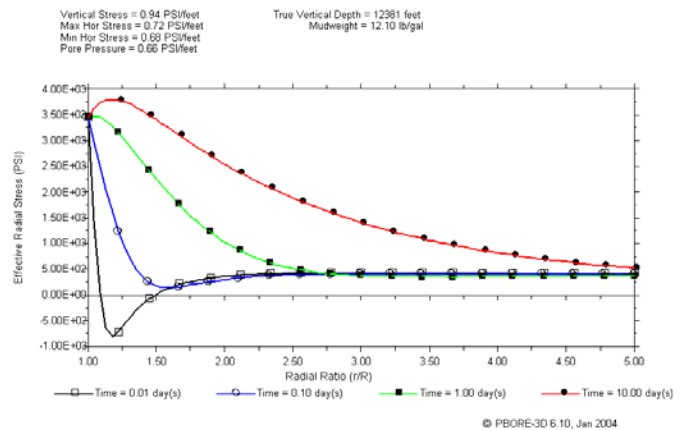


Fig. 5 - Spatiotemporal variation of effective radial stress when the pumps have been shut off after the near-wellbore pore pressure has equilibrated with the ECD at TVD = 12,381 ft.

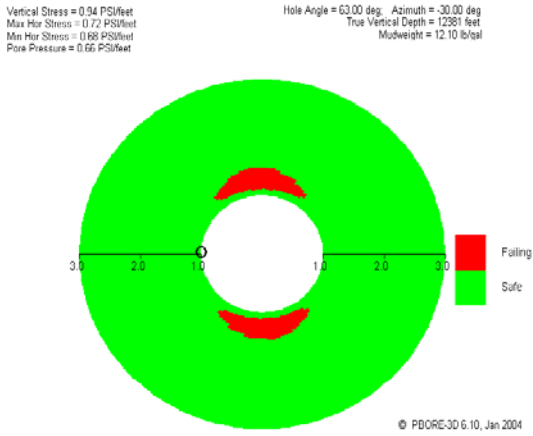


Fig. 6 - Circumferential tensile failure when the pumps have been turned off after the near-wellbore pore pressure equilibrates with the ECD at TVD = 12,381 ft.

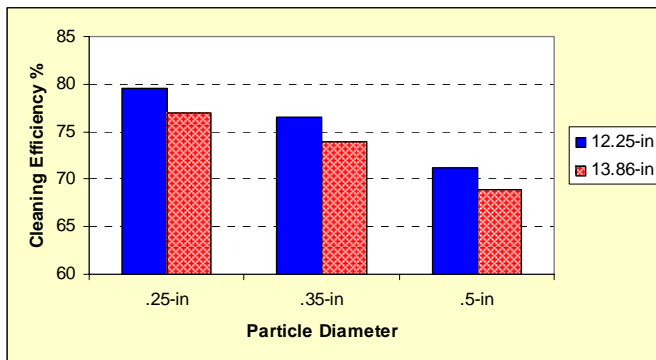


Figure 7 – Predicted particle cleaning efficiencies by particle size for 2 average hole sizes resulting from breakouts due to circumferential tensile failure effects.