



Integration of Hydraulic and Wellbore Stability Modeling: The Next Step Forward

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Abstract

For wells having complex geometry or projected high degree of drilling difficulty, extensive pre-well planning is necessary to optimize key drilling and drilling fluid parameters. These simulations in the well construction process are typically handled in a single fashion and include:

- Hole cleaning optimization
- Hydraulics/equivalent circulating density (ECD) optimization
- Wellbore stability modeling (WBS)
- Torque and drag modeling
- Circulating temperature modeling

Heretofore, predictions of wellbore stability have used surface drilling fluid density as a key input parameter. However, in the normal drilling process, the wellbore wall rarely experiences the surface drilling fluid density, but rather a higher density reflecting the ECD or sometimes a lower density caused by swab effects. Especially for oil-based muds (OBM) or synthetic-based (SBM) muds, the effects of compressibility and thermal expansion on the density of the drilling fluid components cannot be ignored. Also, the impact of drilling fluid-rock interaction on wellbore (in)stability must be accounted for while estimating the safe operating mud window.

In this paper, the next logical step-change in the simulation of these complex projects is introduced and discussed. The drilling fluid hydraulics captured in the drilling operations are inserted into the wellbore stability simulations to estimate the effect of drilling operations on wellbore stability, thereby providing a more realistic assessment of drilling operations on the overall stability of the wellbore while it is being drilled.

Introduction

Recently for an extended-reach drilling (ERD) well in the North Sea, hole cleaning and hydraulics optimization were coupled with wellbore stability modeling to produce a more comprehensive analysis of a large-diameter interval to be drilled with water-based drilling fluid.^{1,2} In that study, a fully coupled wellbore stability analysis was used to estimate the minimum drilling fluid density to

prevent shear collapse and the maximum density to prevent formation fracturing during initial stages of the drilling operation.² In that study, it was determined that a problematic shale zone at $\pm 13,000$ ft TVD could be drilled more safely with a lower angle of penetration (65° vs. the originally planned 85°). The resulting changes required a new wellpath design, one that required a higher kick-off point and shallower tangent in the large-diameter interval. Once the optimized wellpath and corresponding safe mud weight window were identified, the hydraulic and hole cleaning optimization simulations were performed and recommended pump rates, drill pipe rotation speeds, rates of penetration (ROP), etc. were determined. The operator then used the recommendations made in the WBS and hydraulic modeling processes to successfully drill the large-diameter interval with water-based mud (WBM).

In this paper, the hydraulics used in the actual drilling process are inserted in the wellbore stability modeling to re-evaluate the effects of drilling operations on wellbore stability near the bottom of the 12.25-in. interval at 12,381 ft TVD. 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} This interval was drilled with a low-toxicity mineral oil-based (LTOBM) drilling fluid. Changes in key drilling parameters such as pump rate, drill string rotation speed, and ROP were made in a 'what-if' fashion to determine their relative effects on wellbore stability. Key areas addressed in this study include:

- The predicted safe operating window between formation collapse and fracture gradient while drilling
- The polar stability chart for wellpath optimization while drilling the problematic shale near 12,381 ft TVD
- The potential for localized circumferential tensile failure with cessation of mud circulation and ECD effects
- Surge/swab effects on time-dependent wellbore stability

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, 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 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 downhole density was 0.13 lbm/gal lighter than that measured at surface, as shown in **Fig. 1**. 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 fracturization was determined. **Fig. 2** shows the safe operating window while drilling predicted from the chemoporoelastic wellbore stability modeling. 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. 3** the various mud densities and ECD values are detailed for the modeled case.

Fig. 4 shows the stability chart the chemoporoelastic wellbore stability model produces: the minimum mud weights required to prevent hole collapse for different orientations of the wellbore relative to that of the in-situ stresses. 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, as seen in **Fig. 4**. 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

Surge and Swab Effects

The effects of surge and swab are also investigated in terms of wellbore stability. In the case discussed here, the effects of a 0.3 lbm/gal swab, equivalent to POOH at 60 ft/min, was calculated using hydraulic modeling. Wellbore stability simulations using chemoporoelastic methods were then performed. Time-dependency is included in this simulation to demonstrate the progressive collapse failure of the borehole. In **Fig. 5a**, the predicted wellbore collapse is modeled for a short interval of 2 hr. under swab conditions. Here, wellbore failure principally along one axis is predicted, with breakouts of 2-3 in. maximum. **Fig. 5b** contains the results after a period of 24 hr. and predicts failure along nearly the entire wellbore perimeter. While it would be quite rare to maintain swab conditions for 24 hr., the results are useful in that they show wellbore failure increasing over time.

Radial Stress Variations

In standard drilling practice, the static drilling fluid density should always be greater than pore pressure. However, when a drilling fluid is circulated in a wellbore, the near-wellbore pore pressures approach over time the fluid ECD. The degree to which this pressure penetration occurs is dependent upon the efficiency of the barrier (filter cake, pore plugging with specially-selected solid materials, etc.) present 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 radial stresses. In **Fig. 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. Thereafter, the radial stresses become positive once again as pressure differentials equilibrate. While a single case as that modeled here is not considered severe, repeated relaxation of radial stresses (as in rapid sequences of turning the mud pumps on and off or as in the events modeled followed by a swab incident) increases the likelihood of circumferential tensile failure, as shown in **Fig. 7**.

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 chemoporaelastic wellbore stability model can be used to better understand fluid and rock interactions.
- A more refined safe operating window between formation collapse and fracturization 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

Acknowledgements

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References

1. Hemphill, T. and Tare, U.: "Extensive Pre-Well Integrated Modeling Aids in Successful Drilling of Challenging Well: A Case Study," paper AADE-010NC-HO-18 presented at the 2001 AADE National Drilling Conference, Houston, 27-29 March.
2. Stawaicz, R., Taylor, S., Hemphill, T., Tare, U., Morton, K., and Valentine, T.: "Successfully Replacing Oil-Based Drilling Fluids with Water-Based Drilling Fluids: Case Study Demonstrates Value of Extensive Planning and Execution in an Extended Reach Well," *SPE D&C* (December 2003) 18:4, 332-339.
3. Abousleiman, Y., Ekbote, S. and Tare, U.: "Time-Dependent Wellbore (In)Stability Predictions: Theory and Case Study", paper SPE 62796 presented at the 2000 IADC/SPE Asia Pacific Drilling Technology, Kuala Lumpur, Malaysia, 11-13 September.
4. Mody, H. and Hale, A.H.: "A Borehole Stability Model to Couple the Mechanics and Chemistry of Drilling Fluid Shale Interaction," paper SPE 25728, presented at the 1993 SPE/IADC Drilling Conference, Amsterdam, 23-25 February.
5. Nair, R.: "The Poromechanics of Naturally Fractured Rock Formations: A Finite Element Approach," *Ph.D. Diss.*, The University of Oklahoma, 2003.

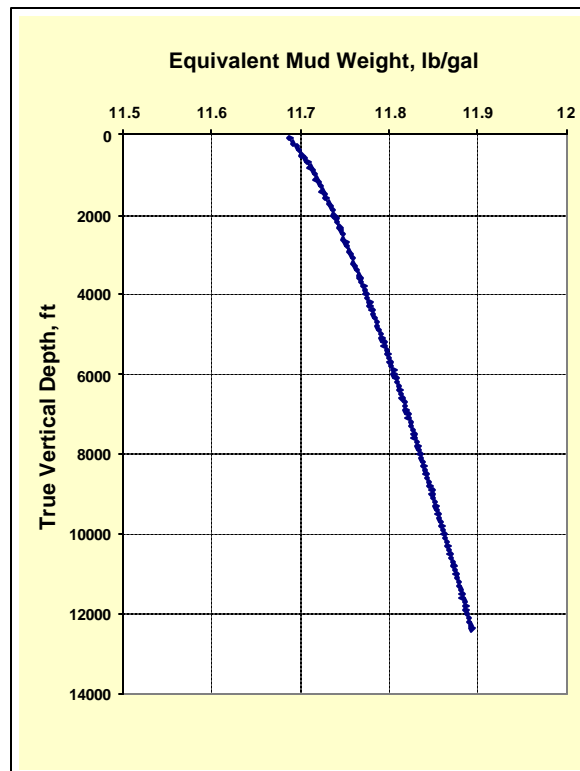


Fig. 1- Predicted downhole static mud density as function of temperature and pressure.

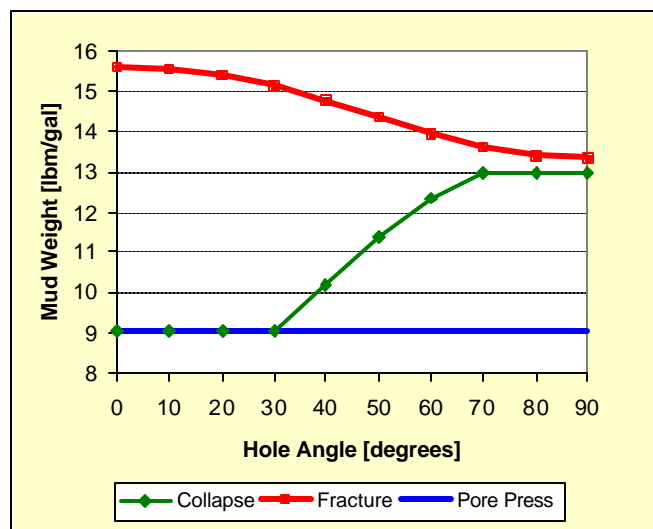


Fig. 2 – Mud weight as a function of hole angle for the 12.25-in. interval at TVD = 12,381 ft., mud activity = 0.77.

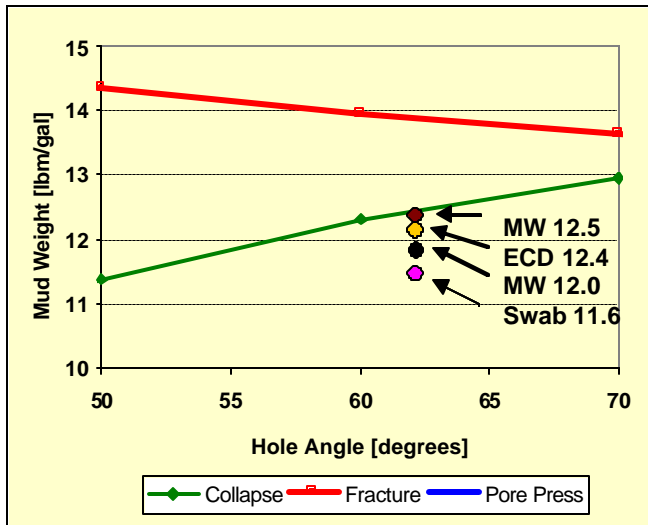
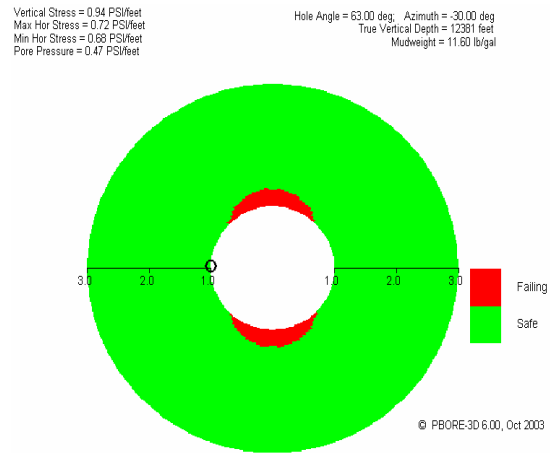
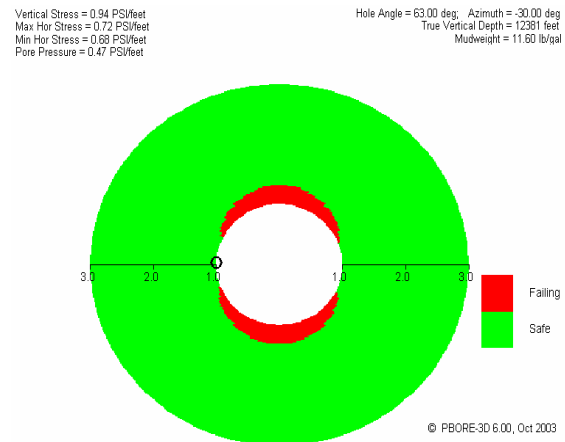


Fig. 3 - Drilling fluid densities, ECD, and swab at 63° deviation (12.25-in. interval at TVD = 12,381 ft., mud activity = 0.77).



(5a)



(5b)

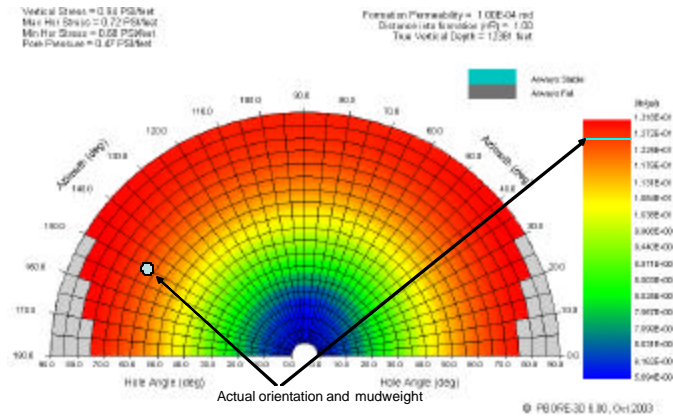


Fig. 4 - Stability chart showing minimum mud weight required to prevent collapse as a function of wellbore orientation at TVD = 12,381 ft., mud activity = 0.77.

Fig. 5 - Progressive collapse failure of the wellbore from 2 hr. (a) to 24-hr. (b) with ECD = 11.6 lbm/gal.

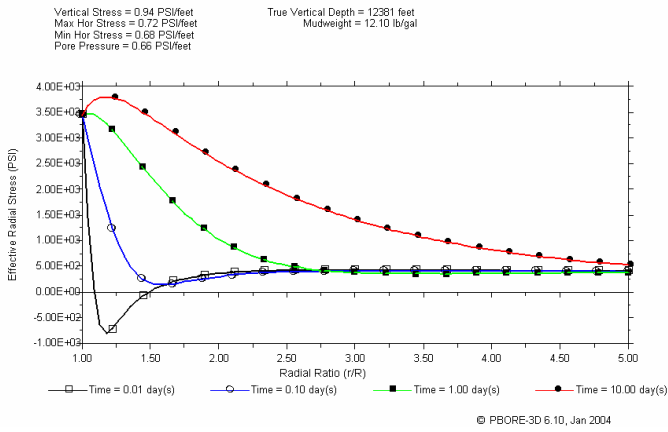


Fig. 6 - Spatiotemporal variation of effective radial stress when the pumps have been shut off after the near-wellbore pore pressure has equilibrated with the ECD at TVD = 12,381 ft.

Vertical Stress = 0.94 PSI/feet
 Max Hor Stress = 0.72 PSI/feet
 Min Hor Stress = 0.68 PSI/feet
 Pore Pressure = 0.66 PSI/feet

Hole Angle = 63.00 deg Azimuth = -30.00 deg
 True Vertical Depth = 12381 feet
 Mudweight = 12.10 lb/gal

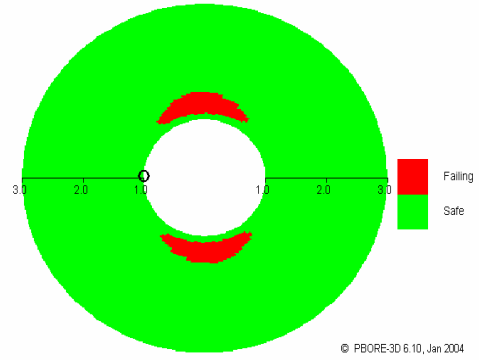


Fig. 7 - Circumferential tensile failure when the pumps have been turned off after the near-wellbore pore pressure equilibrates with the ECD at TVD = 12,381 ft.