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Use of Reservoir Engineering Data in Wellbore Stability Analysis: A Case from Offshore Deepwater Angola

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Abstract

Data required for wellbore stability analysis can be found from a number of sources: rock properties measured in the laboratory, client-supplied in-house data, geomechanical studies, etc. In a recent effort to better predict the safe drilling window for wellbore stability, information was obtained from reservoir engineering data. This data was originally used to analyze sand production potential from a weak sandstone reservoir, offshore deepwater Angola. However, since the information required to predict the degree of 'sanding' in a reservoir to be drilled in an upcoming drilling program requires much of the same rock data as the wellbore stability modeling, the data was used to better predict the safe drilling window for drilling in the reservoir.

In determining the safe drilling window, the hole collapse and fracture gradient pressures were calculated as functions of hole angle and azimuth. In this modeling, all possible combinations of hole angle and azimuth were investigated, and potential wellbore instability could easily be determined. The 100% permeable and 100% impermeable cases were also investigated, in order to highlight the effect of the sandstone permeability on changes in the safe drilling window.

This paper will show how reservoir engineering data can also be used to determine the safe drilling window. With little extra cost, using the same data in two different areas (production engineering and drilling) can greatly benefit the operator through maximizing use of resources.

Introduction

To better understand the potential sanding problems that could result while producing a reservoir offshore, Angola, the operator submitted core samples to a rock laboratory for testing. The operator wanted precise information on rock properties, both mechanical and chemical[1]. For determination of rock mechanical properties, axial and triaxial loading tests were run. Key mechanical properties obtained from the tests[2] included :

- the reservoir rock internal friction angle
- cohesive strength
- Young's modulus
- Poisson's ratio
- Unconfined compressive strength (UCS)

Measured rock chemical properties included:

- Formation connate water salinity
- Total ion concentration
- Pore volume compressibility

For the reservoir engineers, the objective of the tests was to determine to what degree a 'sanding' problem could be expected to occur while producing in the reservoir, and what type of production technique would be most stable (gravel packing, open hole completion, etc.). Of particular interest to those involved in the drilling of the reservoir (long before initiation of production operations) were the rock mechanical properties, since with these properties the boundaries of the safe drilling window could be determined for future wells drilled in reservoirs containing rock similar to that measured in the laboratory tests.

The Safe Drilling Window

In drilling operations, the safe drilling window for a particular formation in question is defined as the range in drilling fluid density between the minimum needed to prevent compressive shear failure of the rock and the minimum required to initiate fracturing of the rock.

In addition to rock mechanical properties, the magnitude of the safe drilling window can be affected by the angle of deviation used to drill the formation and the azimuthal direction. Generally speaking, the higher the angle of deviation in a formation the narrower will be the safe drilling window. Also those wells drilled in the azimuthal direction of the maximum horizontal stress (given a maximum stress exists that is higher in magnitude than the minimum horizontal stress) will exhibit more narrow safe drilling windows.

Examples of such safe drilling windows in previously published work can be found in **Figures 1 and 2**. In **Figure 1**, the safe drilling window, as modeled treating the rock as an elastic medium, is quite large. As long as drilling fluid density / Equivalent Circulating Density

(ECD) is maintained between 12 and 15 lbm/gal, the wellbore is expected to remain stable. A very different case is seen in **Figure 2**. Here the safe drilling window is very wide except at the high angles of deviation, where the magnitude of the safe drilling window is approximately 0.4 lbm/gal at a deviation angle of 85 degrees. Assuming ECD while drilling alone would increase downhole density by at least 0.4 lbm/gal, violation of the safe drilling window would be predicted and fracture initiation could easily be expected at elevated deviation angles. In this second case, the only viable option to the operator was to redesign the well profile so the problematic formation would be drilled with lower angles of deviation.

Use of Drilling Fluid Hydraulic Modeling

In order to gauge the effects of drilling fluid hydraulics on the safe drilling window, extensive hydraulic modeling of drilling fluid properties used while drilling is a standard procedure. In this modeling, ECD and/or the Equivalent Static Density (ESD) is used rather than the surface mud weight, as the pressure the formations downhole experience is controlled by ECD in dynamic cases and ESD in static cases. Previous papers[3,4] have discussed the importance of using ECD and ESD over surface mud weight in wellbore stability simulations.

In this hydraulic modeling, static and dynamic temperature simulators are used to develop the well temperature profile versus depth. With use of invert emulsion drilling fluids, often the static downhole density of the drilling fluid is less than that measured at surface due to the thermal expansion properties of the base fluid. Conversely in deepwater drilling with invert emulsions, the downhole ESD can be higher than the density measured at surface. Water-based drilling fluids usually exhibit less of an effect of temperature and pressure on downhole densities. With proper modeling, the downhole density of any drilling fluid can be well-predicted for better mapping of the well's safe drilling window. **Figure 3** contains modeling results for an invert emulsion used in the North Sea, where high friction in the annulus resulted in higher circulating temperatures and consequently reduced downhole fluid densities. Instead of having a 12.0 lbm/gal density, as measured on surface, the predicted downhole density was calculated to be 11.9 lbm/gal, a reduction of 0.1 lbm/gal.

In addition to downhole density prediction, drilling fluid hydraulic modeling can also be used to predict the effect of the following items on ECD:

- Surge and swab of the drillpipe
- Hole cleaning efficiency of drilled cuttings
- Drillpipe rotation speed
- Rotary drilling versus slide drilling

With an accurate assessment of the drilling fluid downhole hydraulics, the associated effects of ECD/ESD on possible violation of the safe drilling window can be better predicted.

Drilling in the Reservoir, Offshore Angola

With the rock mechanical properties, field information, and estimates of drilling fluid circulating hydraulics in hand, the mapping of the safe drilling window for the reservoir was undertaken. This mapping included calculations for the following items:

- hole collapse pressures
- pressures required to initiate fractures
- the effects of hole angle, azimuth, and formation permeability on the abovementioned pressures

Base case parameters for wellbore stability modeling in the reservoir are found in **Table 1**. While the overburden stress could be calculated, the minimum horizontal stress was taken to be equal to the fracture gradient for the TVD of the reservoir. In this stress-relaxed drilling environment offshore Angola, the maximum and minimum horizontal stresses are nearly equal in magnitude. For purposes of this study, it was assumed the maximum horizontal stress was 5% greater than the minimum horizontal stress. Rock tensile strengths were assumed to be zero (0), a value typically used in wellbore stability simulations. A vertical wellbore was assumed for the base case.

From the data in **Table 1**, the reader can see that the measured rock cohesive strength of 160 psi (1.1 MPa) was low, indicating a weak, poorly-cemented rock matrix. In their report to the Operator regarding the core tests, the rock researchers noted that this value was most likely on the low side and estimated the true rock cohesive strength to be somewhere between 145 and 435 psi (1-3 MPa).

Wellbore Stability Modeling for the Base Case

Using the base case parameters in **Table 1**, the safe drilling window was modeled. For the specific formation studied here, the modified Lade criterion was selected as the most appropriate criterion to use for rock failure. Failure in the stability modeling exercise is predicted to occur when the wellbore wall hoop stress falls below zero (0) psi or Pa. The safe drilling window was determined for a fully-permeable wall and for a non-permeable wellbore wall. By using these two extremes, the upper and lower bounds for hole collapse pressures and fracture initiation pressures can be identified.

For the hole collapse pressures in the vertical wellbore, the results shown in **Figure 4** for the 100% permeable case showed a minimum ECD/ESD of 1.58 sg (13.2 lbm/gal) would be required to maintain a stable wellbore. For the 100% impermeable case shown in **Figure 5**, a minimum ECD/ESD of 1.16 sg (9.7 lbm/gal) would be required. Less density is required to maintain stability in the 100% impermeable case, as no fluid from the wellbore is allowed to enter the wellbore wall and destabilize the rock matrix. Given an ECD of 1.2 sg (10.0

lbm/gal), the wellbore stability modeling predicts some hole collapse for the 100% permeable vertical case and no instability for the fully-impermeable vertical case.

In terms of pressures required to initiate fracturing in the vertical wellbore, the results for the 2 permeability cases are given below:

- 100% permeable case: 1.37 sg (11.4 lbm/gal), shown in **Figure 6**
- 100% impermeable case: >1.6 sg (13.4 lbm/gal), shown in **Figure 7**

As seen earlier for the hole collapse pressures, these results show a lower failure threshold for the 100% permeable case compared to the fully-impermeable case. With an ECD of 1.2 sg (10.0 lbm/gal), no problems are seen for fracturing of the rock in these simulations. Any hole stability problems would result from inadequate densities to prevent hole collapse.

In modeling for hole collapse, the effects of hole angle and azimuth for the 100% permeable case are shown in **Figure 8** (fully permeable case). In these polar charts, hole angle is read in 10-deg deviation increments from the center going outward and the hole azimuths are read radially, with true north having a defined azimuth of 0/360 degrees. The results indicate that, with the rock properties for the base case, hole collapse would be inevitable at any hole angle and azimuth combination. Quite a different scenario is seen for the fully-impermeable case, as is shown in **Figure 9**. Here, the hole stability can be maintained at all hole angle/azimuth combinations provided a minimum ECD/ESD is maintained.

Because drilling operations on previous wells have not experienced significant hole collapse in the studied section, it was assumed that the rock cohesive strength is actually higher than that measured in the laboratory (as the laboratory researchers initially thought). Hence the decision to expand the scope of the wellbore stability simulations to include higher cohesive strengths of 290 psi (2 MPa) and 435 psi (3MPa) was made.

Wellbore Stability Modeling Using Higher Rock Cohesive Strengths

As seen earlier, hole collapse in the fully-permeable formation presents a higher potential than that for the fully-impermeable case, and warrants further examination here. For the C_0 = 290 psi (2 MPa) case, results in **Figure 10** showed a stable wellbore at all hole angle/azimuth combinations. Due to the higher cohesive strength used in the modeling, less ECD/ESD is predicted to maintain wellbore stability while drilling.

Increasing the C_0 to 435 psi (3 MPa) shows stability at all combinations of hole angle / azimuth, as shown in **Figure 11**. Again, less ECD/ESD is required to maintain stability than in the previous case.

Because these last results are simulations only, they need to be calibrated with field data for maximum benefit. Any experiences of hole collapse in the field – coupled with actual drilling data - could then be used to calibrate the modeling: especially a good value for the rock cohesive strength for the fully-permeable case.

Conclusions and Recommendations

In this paper, a number of important points for better understanding of wellbore stability in the field are noted:

- Rock parameters used in reservoir modeling can be used to model wellbore stability while drilling in the same formations. Many of the parameters are identical to both discisplines.
- Downhole drilling fluid density, as given by ECD while circulating and drilling or ESD while the fluid is static are key parameters to monitor in wellbore stability predictions. Surface density was not found to be a useful tool.
- All else being equal, maintaining wellbore stability in permeable formations will require higher densities (ECD or ESD) than will impermeable formations.
- All possible combinations of hole angle and azimuth can be modeled for their effects on wellbore stability (hole collapse and fracture initiation pressures).
- Results of the modeling simulations can be calibrated with actual field drilling data for those cases where the value for a specific rock property is not exactly known. Occurrences of hole collapse, tight hole, lost circulation, etc. should be studied thoroughly.

Acknowledgments

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Nomenclature

Define symbols used in the text here unless they are explained in the body of the text. Use units where appropriate.

C_0 = Rock cohesive strength
ECD = Equivalent circulating density
ESD = Equivalent static density
TVD = Total vertical depth

References

1. Sonangol internal report
2. "Rock Mechanical Study of Reservoir Formation – Angola" (internal study)
3. Hemphill, T., "Integrated Management of the Safe Drilling Window: Wellbore Stability Is More Than Just Fluid Density", paper SPE 94732 presented at the 2005 SPE Latin Ametrican and Caribbean Petroleum Engineering Conference in Rio de Janeiro (20-23 June 2005).
4. Hemphill, T. and Nair, R., "Integrating Optimization of Drilling Parameters with Wellbore Stability", paper AADE-05-NTCE-10 presented at the AADE 2005 National Technical Conference and Exhibition in Houston (5-7 April).

Table 1 – Key Parameters Used in Study

Parameter	Value
Overburden (psi/ft)	0.686
Min. horizontal stress (psi/ft)	0.603
Max. horizontal stress (psi/ft)	0.633
Rock C_0 (psi)	145 - 435
Rock internal friction angle (deg)	28
Rock porosity (% v/v)	25
Rock permeability (mD)	300-1000
Poisson's ratio	0.265
Young's modulus (psi)	900000
ECD (lbm/gal)	10.0
Hole ID (in)	8.5

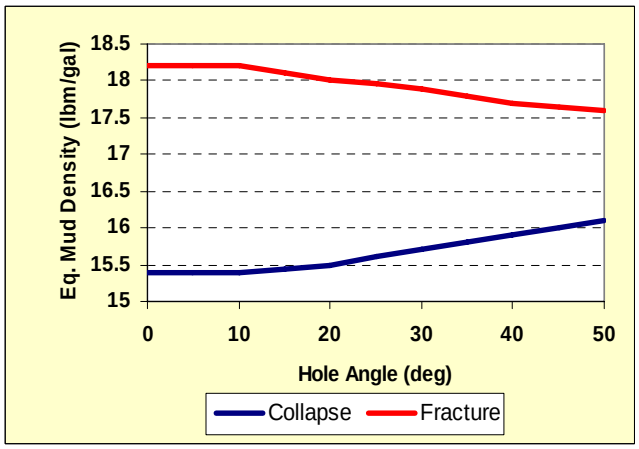

Figure 1 – Example of wide safe drilling window.

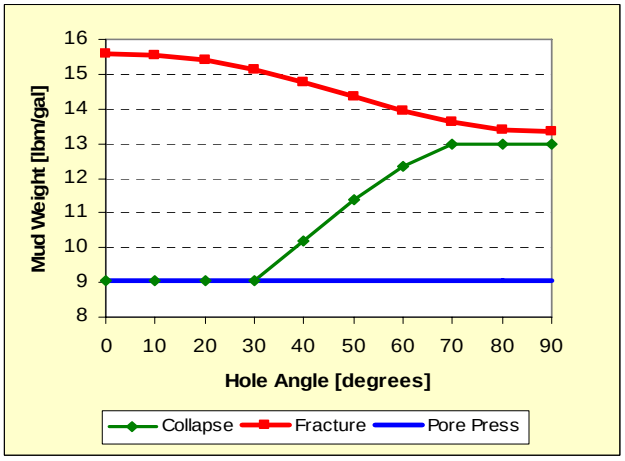

Figure 2 – Example of a very narrow safe drilling window for hole angles 70-90 degrees from vertical.

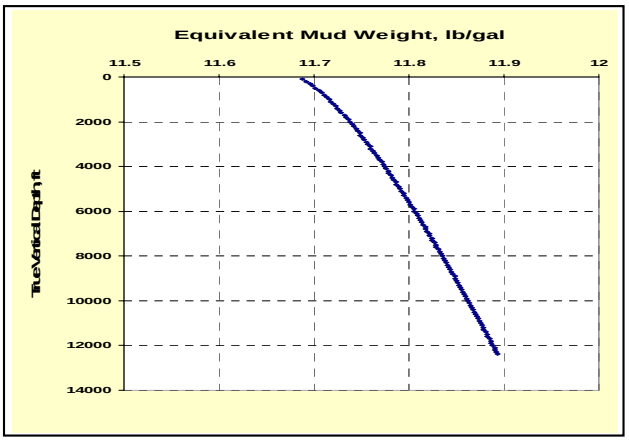

Figure 3 – Modeling example of downhole ESD. While surface density = 12.0 lbm/gal, the density at TD = 11.9 lbm/gal.

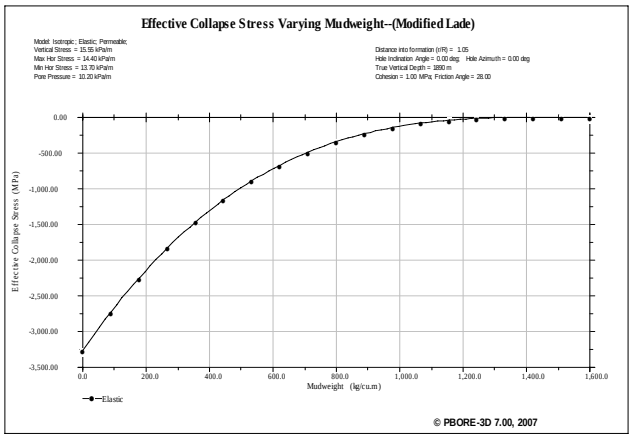

Figure 4 - Predicted hole collapse stress for 100% permeable base case. Hole collapse predicted for ECD < 1.58 sg.

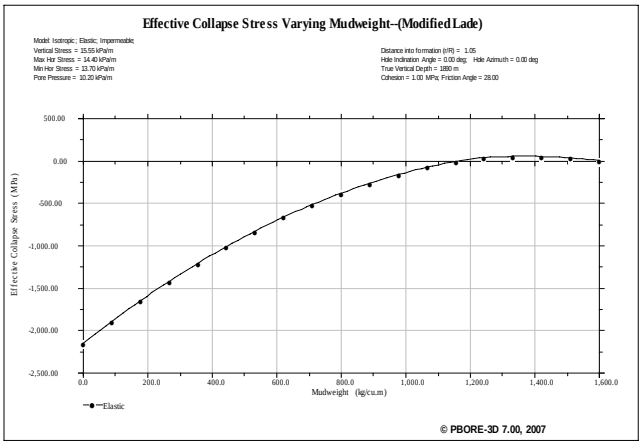

Figure 5 – Predicted hole collapse stress for 100% impermeable base case. Hole collapse predicted for ECD< 1.16 sg.

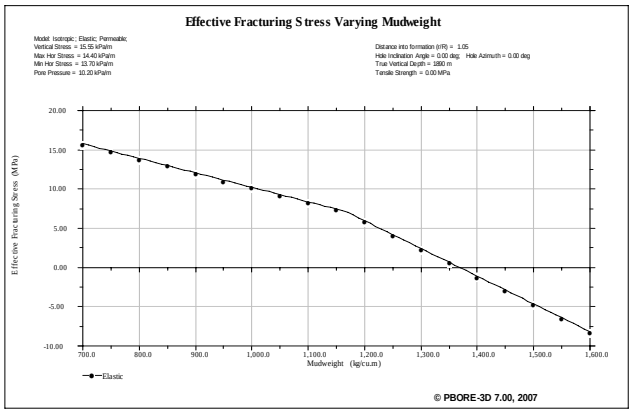

Figure 6 – Predicted fracturing stress for 100% permeable base case. Fracturing predicted for ECD = 1.37 sg

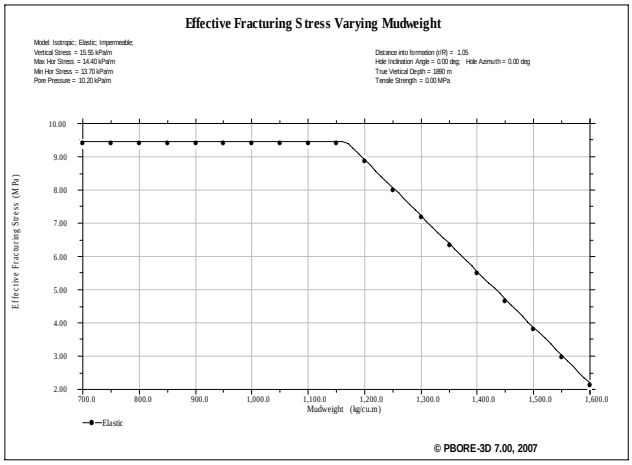

Figure 7 – Predicted fracturing stress for 100% impermeable base case. No fracturing predicted for ECD = 1.6 sg.

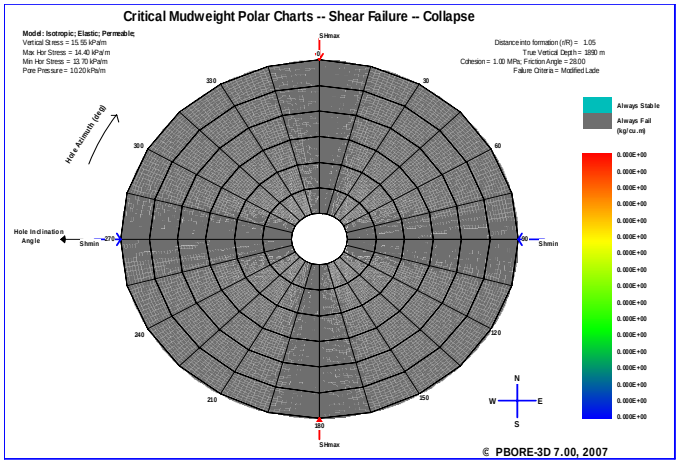

Figure 8 – Hole collapse predictions for all angle/azimuth combinations, 100% permeable base case. Catastrophic hole collapse predicted for all combinations.

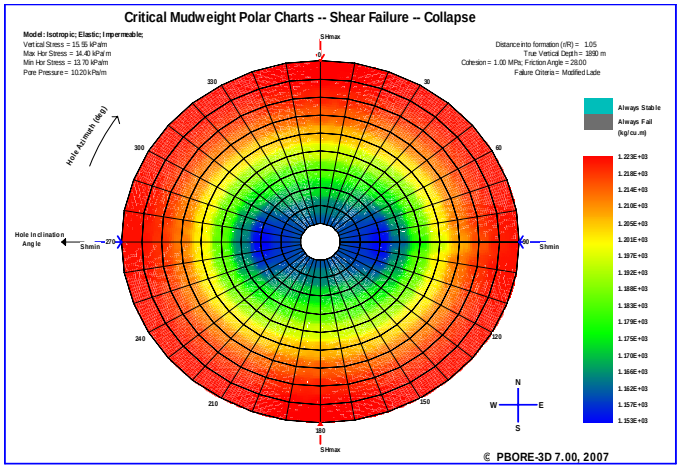

Figure 9 – Hole collapse predictions for all angle/azimuth combinations, 100% impermeable base case. Hole stability predicted for ECD 1.15-1.22 sg.

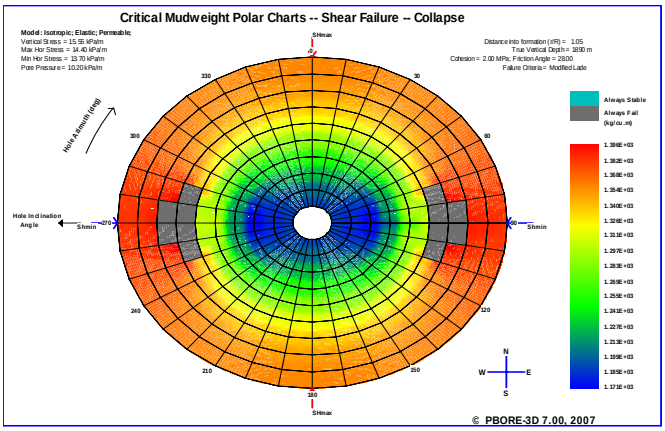

Figure 10 – Hole collapse predictions for all angle/azimuth combinations, C_0=290 psi, 100% permeable case.

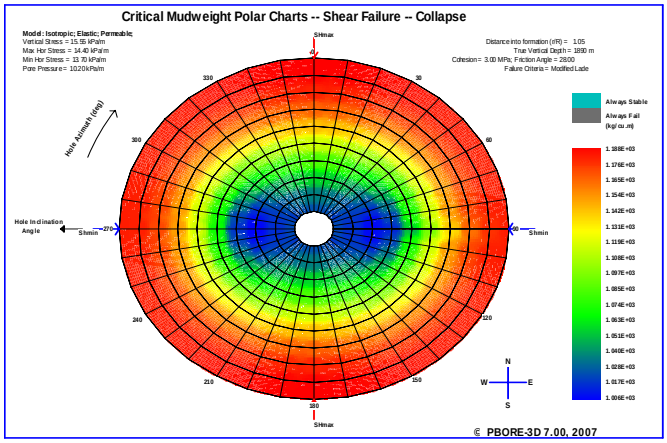

Figure 11 – Hole collapse predictions for all angle/azimuth combinations, C_0 = 435 psi, 100% permeable case. Hole stable with ECD 1.0 to 1.08 sg.