Effect of Water Depth on Bridging Tendencies in Ultradeepwater Blowouts in Gulf of Mexico

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Abstract

A blowout is an uncontrolled flow of reservoir fluids into the wellbore to the surface, causing serious, sometimes catastrophic, problems in different types of petroleum engineering operations. If the formation’s strength is low and the pore pressure is high, bridging can be a very effective method for blowout containment. In this method, the formation caves into the open hole or onto the casing and stops the flow of the formation’s fluid, either naturally or intentionally. This method can be effective in deepwater blowouts where the formation has high pore pressure and considerable shale intervals with low strength.

In this paper, wellbore stability and fluid flow performance subroutines have been developed with Visual Basic for Applications (VBA) programming. By integrating the subroutines together, we made a simulation tool to predict wellbore stability during blowouts and, consequently, predict wellbore bridging during normal and blowout situations. Then we used a real case in the country of Brunei to investigate a field case of a bridged wellbore to validate the simulator.

Based on this simulation tool we are able to determine the potential location of bridging during the blowout situation and compared the model with real data and field observations during normal and blowout situations. The difference between our simulator and existing models is that existing simulators only determine breakouts in static situations not during the blowout.

In the final part of this paper we studied the effect of water depth on bridging tendency during a blowout for the deepwater Gulf of Mexico (GOM). Since we could not find much real data in this area, we used general trends and correlations related to the GOM for parts of our study. The results of our study showed that water depth delays the occurrences of breakout in the wellbore during blowouts (i.e. for greater depth of water, wellbore collapse occurs farther below the mudline). However, the depth in which collapse occurs is different for different maximum horizontal stress amounts.

Introduction

Wellbore bridging is responsible for controlling more offshore blowouts than any other procedure. However the mechanisms of bridging are known mostly qualitatively and there have been no engineering tools for predicting wellbore bridging during blowouts. We have conducted a study and developed a tool where wellbore collapse and bridging can be predicted during blowouts. The tool that we developed will aid the operators in contingency planning that would be used in the event of a blowout.

We have developed a simulation tool with the specific boundary conditions that are expected during blowouts. It can be used to predict wellbore collapse and bridging during a blowout. We have analyzed case histories and compared the observed bridging locations with the modeling results and have studied the effect of water depth on bridging tendency in deepwater Gulf of Mexico (GOM).

Our geomechanical model has four main subroutines: in-situ field stresses acting in the wellbore region, a computational module that calculates the fluid pressure profile along the wellbore, formation properties based on sonic interval transient time, and finally the forth subroutine to integrate the previous three modules. In order to study the water depth effect on wellbore bridging in the GOM we have used general sand-shale velocity relationship for the GOM under normal pressure condition (Gardner et al., 1974). Then we simulated the pore pressure and fracture pressure gradients in the GOM for different depths below the mudline as well as different water depths.

Water Depth Effect on Wellbore Bridging

Since we could not find real data for the deepwater GOM that could be used in our study, we used general trends and probable values for this study. Some assumptions we have taken in this approach are:

- Wellbore geometry = vertical.
- Wellbore diameter = 7 7/8 in.
- Formation = shale.
- No mud in wellbore during blowout.
- Open flow path during blowout (no back pressure).
- Fixed outlet pressure = hydrostatic pressure at seabed.
- Gas gravity (air=1) = 0.65.
Geomechanical Model

Generally, a geomechanical model consists of the magnitude and orientation of the three principal stresses, the pore pressure, and the uniaxial compressive rock strength.

In our approach to analyze the wellbore bridging, we constructed a geomechanical model suitable for our case with the four main subroutines we developed. The first one is related to the in-situ field stresses acting in the wellbore region. The second subroutine is a computational module that calculates the fluid pressure profile along the wellbore. (The other alternative for this subroutine is the fluid pressure profile obtained from observations or any other fluid flow simulator.) The third subroutine has been designed to determine the formation properties from sonic interval transient time, and the fourth subroutine has been created to integrate the previous three modules into a bridging simulation. As input data in our calculations, we have used well-specific data such as TVD, pore pressure, inclination, and angle between maximum horizontal stress and wellbore direction.

In-Situ Field Stresses.

Overburden Stress. In normal practices it is quite common to assume overburden gradient 1 psi/ft. However, this is a high average value for a nonconstant variable, and it can be seriously in error in some areas, like the gulf coast at shallow depths. According to Eaton, in the gulf coast area the average overburden stress gradient does not equal 1 psi/ft; instead it is about 0.85 psi/ft near the surface and increases smoothly to 1 psi/ft at about 20,000 ft of depth.

To apply the effect of different overburden gradients for different depths in our study, we used Eaton’s overburden stress gradient for normally compacted gulf coast formations.

However, Eaton’s curve is not for deepwater offshore applications, and hydrostatic pressure of water is not considered. Therefore, in our case for any depth below the mudline the maximum vertical stress is the summation of overburden gradient from Eaton’s curve multiplied by the depth and hydrostatic pressure of sea water:

\[ S_v = g_{wb} \times D + 0.0519 \times 8.33 \times WD, \]

Where \( S_v \) is vertical stress, \( g_{wb} \) is Eaton’s overburden gradient, \( D \) is depth below mudline, and \( WD \) is water depth.

Maximum Horizontal Stress. Since we could not find any correlation for maximum horizontal stress for deepwater GOM, we assumed three different assumptions for calculating maximum horizontal stress.

First we assumed that for any depth the maximum horizontal stress is equal to the maximum vertical stress at that depth. This is a good assumption for areas characterized by normal faulting systems.

The second assumption is based on the strike-slip faulting system condition. To calculate the maximum horizontal stress in this condition, we used Anderson’s faulting theory:

\[ \frac{\sigma_{hr}}{\sigma_3} = \frac{S_h - p_p}{S_h - p_p} \leq \left( \frac{\mu}{\sigma_3} \right)^2, \]

Where \( S_h \) is maximum horizontal stress, \( \sigma_3 \) is maximum normal stress, \( p_p \) is confining pressure, and \( \mu \) is coefficient of internal friction.

According to the laboratory tests, a coefficient of friction of 0.6 to 1 is applicable in any faulting system. If we assume a coefficient of friction equal to 0.6, for the case of frictional equilibrium we can rewrite the above equation as:

\[ S_h = 3.1 \times S_v - 2.1 \times p_p, \]

Finally, in the third case we assumed that the maximum horizontal stress is equal to the minimum horizontal stress.

Minimum Horizontal Stress. We used generic data from the deepwater GOM to obtain the fracture gradients for different seawater depths. Then we assumed that for any specific depth below mudline, the minimum horizontal stress is equal to depth multiplied by the fracture gradient at that depth.

Rock Mechanical Properties.

Angle of Internal Friction and Cohesion. To obtain the angle of internal friction, \( \phi \), and cohesion, \( S_0 \), of shale, Gardner’s general sand/shale velocity relationship for the GOM under normal pressure conditions has been used.

Having the compressional sonic velocity from general sand/shale velocity trend in the GOM, we obtained the angle of internal friction, \( \phi \), and cohesion, \( S_0 \), from Manohar’s shale strength correlation. These relations (Eq. 4 and Eq. 5) were developed using an extensive shale database:

\[ \sin \phi = \frac{(V_p - 1)}{(V_p + 1)}, \]

\[ S_0 = \frac{5(V_p - 1)}{\sqrt{V_p}}, \]

Where \( V_p \) is compressional sonic velocity of the shale.

Poisson’s Ratio. Another important variable which changes with depth is Poisson’s ratio. The most frequent average value of Poisson’s ratio being used for rocks is 0.25, but it may cause error where depth changes. The amount of horizontal stress caused by the net overburden is a function of Poisson’s ratio of the rocks.

Based on laboratory experiments, Poisson’s ratio can change from well to well over 0.25, but its value is never greater than 0.5. So it is quite important to use the proper value for Poisson’s ratio according to the field of study. For this reason, we have used Eaton and Eaton’s Poisson ratio for deepwater Gulf of Mexico.

Pore Pressure and Wellbore Pressure. To calculate the pore pressure for different depths below mudline and for different depth of water, we used generic data from deepwater GOM.

Wellbore pressure during a blowout was calculated by our subroutine, which is a computational module that calculates the fluid pressure profile along wellbore. The other alternative for this subroutine is the fluid pressure profile obtained from observations or any other fluid flow simulator.

Bridging Simulation

Using modified-Lade criteria, stresses induced in the vicinity of the wellbore were compared with rock strength to determine the potential locations of fractured or collapsed intervals. We used an elastic model using a 3D generalized plane strain solution to compare the induced stresses and rock
strength. We simulated bridging for water depths of 100, 1,000, 3,000, 5,000, 7,500, and 10,000 ft to determine the effect of water depth on wellbore bridging during blowout. For each water depth we performed the simulation from the seabed to the depth of 20,000 ft below mudline. Because it is assumed that the wellbore is vertical, we considered the critical breakout angle as 90°, and considered any location with breakout angle greater than this critical value as a potential part for wellbore failure or bridging.

**Normal Faulting System:** $S_H > S_V$. Fig. 1 shows the results of our simulation for normal faulting system, where maximum horizontal stress is equal to vertical stress.

This result shows that for the example with 10,000 ft of water depth, breakout angle is more than 90° anywhere below about 2,500 ft below the mudline.

**Strike-Slip Faulting System:** $S_H > S_V$. For this condition in our model, maximum horizontal stress is always the maximum principal stress ($S_H > S_V$). Figs. 4 to 12 show the relation between pore pressure, minimum horizontal stress, maximum horizontal stress, vertical stress, and wellbore pressure for different depths of water.

Results of this simulation show that in this case the critical depth in which the wellbore collapses and breakout occurs is even shallower than the previous situation, and for 10,000 ft of water depth the breakout exceeds 90° everywhere below about 2,500 ft below the mudline (Fig. 2).

**Tectonically Relaxed:** $S_H = S_V$. Results of this simulation for this maximum horizontal stress show that in this case the critical depth at which the wellbore collapses and breakout occurs is deeper than the two other cases, and for 10,000 ft of water depth the breakout occurs below about 3,500 ft of mudline (Fig. 3).

**Discussions, Conclusions, and Recommendations**

We investigated wellbore bridging tendencies for deepwater GOM using general trends and correlations valid for this area. Since breakout is most probable in shale intervals, we conducted our simulation just for shale formations.

Because the most complex factor to determine in a geomechanic model is the maximum horizontal stress and we could not find any correlation for it for the deepwater GOM, we considered three cases for this matter.

In the first assumption, which is valid for any normal faulting system, we assumed that maximum horizontal stress is equal to vertical stress. The second assumption is strike-slip faulting system conditions in which the maximum horizontal stress is the biggest principal stress and vertical stress is the intermediate principal stress. In the third case we assumed that the maximum horizontal stress is equal to minimum horizontal stress which was calculated from the fracture gradient for each depth.

Results of all simulations for all three categories showed that water depth delays the occurrences of critical breakout angle in the wellbore during blowout; that is, for greater depth of water, wellbore collapse occurs at greater depth below mudline. However, the depth in which collapse occurs is different for different maximum horizontal stresses assumed.

For example, in a normal faulting system and for 10,000 ft of water, we will have wellbore bridging everywhere below about 3,000 ft below mudline. For the strike-slip faulting condition, the critical depth where the bridging starts is even shallower at about 2,500 ft below mudline. The third case, which assumes equal maximum and horizontal stress, shows that for this depth of water bridging starts from 3,500 ft below mudline.

Although these results are based on some assumptions we have made and the general trends and correlations that we used for constructing the geomechanical model, our study shows that for this case greater than 4,000 ft below mudline, wellbore bridging will occur in shale intervals if a blowout occurs.

In this research we studied wellbore bridging from the rock-mechanical point of view. We determined collapse potentials in the wellbore, but bridging also depends on other parameters like reservoir performance and solid transportation. As future work, adding these subroutines will make our simulator more robust.

We have developed a tool which can predict the likelihood of wellbore collapse during a blowout which can be utilized in blowout contingency planning.

**Acknowledgments**

The authors would like to thank the National Iranian Oil Company, the Offshore Technology Research, the U.S. Minerals Management and the Research Partnership to Secure Energy for America for sponsoring this project. We would also like to acknowledge the contributions of the late Dr. Serguei Jourine for his contributions to this work.

**Nomenclature**

- $D =$ depth below mudline, ft
- $g_{ob} =$ Eaton’s overburden gradient, psi/ft
- $p_p =$ pore pressure, psi
- $S_0 =$ Mohr-Coulomb cohesion of the material at zero confining pressure, MPa
- $S_h =$ minimum horizontal stress, psi
- $S_{h} =$ maximum horizontal stress, psi
- $S_v =$ vertical stress, psi
- $V_p =$ compressional wave sonic velocity, km/s
- $WD =$ water depth, ft
- $\mu_i =$ coefficient of internal friction, dimensionless
- $\sigma_i =$ maximum normal stress, psi
- $\sigma_f =$ confining pressure, psi
- $\phi_i =$ angle of internal friction, dimensionless

**References**


Fig. 1—Breakout angles during blowout for $S_h = S_v$.

Fig. 2—Breakout angles during blowout for $S_h = 3.1 \times S_v - 2.1 \times P_r$.

Fig. 3—Breakout angles during blowout for $S_r = S_w$. 

BA, Degree

Depth below Mudline, ft

WD=100
WD=1000
WD=3000
WD=5000
WD=7500 ft
WD=10,000 ft

WD=100
WD=1000
WD=3000
WD=5000
WD=7500 ft
WD=10,000 ft

BA, Degree

Depth below Mudline, ft
Fig. 4—In-situ stresses, pore pressure and wellbore pressure for strike-slip faulting case and WD=100 ft.

Fig. 5—In-situ stresses, pore pressure and wellbore pressure for strike-slip faulting case and WD=1000 ft.

Fig. 6—In-situ stresses, pore pressure and wellbore pressure for strike-slip faulting case and WD=3000 ft.

Fig. 7—In-situ stresses, pore pressure and wellbore pressure for strike-slip faulting case and WD=5000 ft.
Fig. 8—In-situ stresses, pore pressure and wellbore pressure for strike-slip faulting case and WD=7500 ft.

Fig. 9—In-situ stresses, pore pressure and wellbore pressure for strike-slip faulting case and WD=10,000 ft.

Fig. 10—In-situ stresses, pore pressure and wellbore pressure for strike-slip faulting case and 260 ft below mudline.

Fig. 11—In-situ stresses, pore pressure and wellbore pressure for strike-slip faulting case and 10,253 ft below mudline.
Fig. 12—In-situ stresses, pore pressure and wellbore pressure for strike-slip faulting case and 20,589 ft below mudline.