NUMERICAL ANALYSIS OF OPEN-HOLE MULTILATERAL COMPLETIONS MINIMIZES THE RISK OF COSTLY JUNCTION FAILURES

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Abstract

This paper discusses the numerical (3D FEA) modeling of openhole, horizontal, multilateral junctions, to evaluate their mechanical stability under various conditions of junction length, junction orientation, in-situ stress, and rock strength, during drilling and production operations. The objective of the numerical analysis is to evaluate the risk of multilateral junction failure associated to changes in the above parameters for: (i) the prediction of minimum rock strength (UCS) required for placing the junction, and (ii) for minimizing the risk of junction failure, under various conditions of drawdown and depletion. Results provide clear guidelines for multilateral junction construction (i.e., multilateral geometry), placement (i.e., minimum required rock strength) and safe conditions of operation (i.e., drawdown and depletion). Results also provide critical conditions of drawdown and depletion as a function of rock strength. Furthermore, 3D FEA results show that because of the asymmetry in the junction geometry, the resulting bending moments that develop along the mother-bore and the lateral wellbores reduce the mechanical stability of the multilateral junction. This effect cannot be adequately represented by 2D plane-strain solutions. The discussed methodology will minimize the risk of junction failures resulting in considerable savings to the operator.

1. Introduction

Completion costs, after well drilling, add significantly to the overall cost for field development. These costs are particularly high for deep-water fields, where they may exceed $2 Million US dollars per well, or be considerably higher when cased multilateral completions are needed. Completion alternatives are selected to optimize productivity while minimizing the risk of mechanical failure, and their selection requires a delicate balance between minimizing costs, maximizing flow performance, and minimizing the risk of catastrophic failure. When considering less costly, open-hole, multilateral completions, the cost reduction and potential increase in productivity may be outweighed by the higher risk of catastrophic failure. Thus, evaluating the viability of openhole junctions is enhanced by detailed

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This paper discusses the stability of openhole, horizontal, multilateral junction, under various conditions of junction length, junction orientation, in-situ stress, rock strength, and drilling or production operations. The objective of the analysis was to evaluate the risk of multilateral junction failure associated to changes in the above parameters, and to evaluate the minimum rock strength (UCS) required for minimizing the risk of junction failure under various conditions of drawdown and depletion.

2. Modeling and Calibration

An elastic-brittle constitutive law with a calibrated 3D Coulomb failure criterion was used, to evaluate the potential for multilateral junction failure. Coulomb parameters of cohesion and friction angle were measured via laboratory analysis. The model was rigorously calibrated against laboratory data of thick-walled cylinder (TWC) failure and subsequently against detailed numerical simulations of openhole horizontal wellbore failure using the Sand 3D computer code (Morita et al., 1989). Calibration results were used to construct a color-coded representation of the conditions of multilateral junction stability and thus to provide a direct visual indication of the risk for junction failure at any particular condition of depletion and drawdown.

Because of the asymmetry of the multilateral junction geometry, three-dimensional numerical simulations are required to evaluate their conditions of deformation and potential failure. Two-dimensional models, although adequate for capturing the interaction between adjacent, coplanar wellbores, do not adequately reflect the stress development at the region of convergence between wells; neither do they capture the stress rotations and consequent bending moments that develop along the junction.

For this work, a hydro-mechanical 3D finite element (FemLab) with coupled elastic deformation and Darcy’s fluid flow was used. The model calculates stress, strain and pore pressure distributions along the entire 3D domain, as resulting from prescribed in-situ stress ($\sigma_x, \sigma_y, \sigma_z$) reservoir pressure ($p_r$) and wellbore pressure ($p_w$) at the boundaries. Results from modeling provide stress (including pore pressure), and strain concentrations around the multilateral junction. These results are used to evaluate regions exceeding the conditions of rock failure. For cases exceeding failure, the required minimum rock strength (UCS) to minimize the risk of failure was also evaluated. Thus, in addition to providing predictions of rock failure, FemLab also provided the critical minimum UCS for constructing a safe multilateral junction.

Two FEA grid models consisting of horizontal, openhole multilateral junctions were constructed to simulate maximum and minimum geometries during drilling. The first case corresponded to a wellbore separation obtained at 25 ft from the mother-bore. The second case corresponded to wellbore separation obtained at 50 ft from the mother-bore. In both cases a three-dimensional region extending 80 x 80 x 40 inches (vertical direction) was used to simulate the region around the junction. The boundary conditions for the reservoir pressure extend a maximum of 40-inches away from the junction. Thus, the equilibrated reservoir pressure profile does not represent the steady state solution of an infinite reservoir. Figure 1 shows an example of the 3D mesh representation for the 25 ft model. The model takes advantage of the vertical symmetry of the problem and uses only the lower half of the junction during numerical computations. The half model contains the complete information of the problem while allowing the use of more refined grid meshes to obtain solutions at a higher resolution. Figure 2 shows an example of the output from a simple simulation (at high drawdown and high depletion). Flow lines are shown in light blue; contours of the fail function are shown color coded. At the wellbore surface, black represents catastrophic failure, red represents onset of failure and yellow represents a low risk of failure. Inserts on the right show values of the flow vectors and the fail function along the end crosssections. Similar values are also shown along the plane view of the junction.

Twenty-three numerical simulations were conducted to evaluate the effect of mother-bore orientation (in relation to the maximum horizontal stress), reservoir depletion, rock type, junction geometry (with lengths of 25 ft and 50 ft prior to hole departure) and the effect of in-situ stress (upper bound and lower bounds). The program also included multiple runs of the code Sand 3D for calibration purposes.

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1 Sand 3D is a 3D FEA model for sand production predictions on vertical and inclined single wellbore completions.
Figure 1. Grid mesh configuration for a 8 ½-inches diameter multilateral junction with 25 ft length prior to well departure. A region of 80 x 80 x 40 inches around the junction is considered.

Figure 2. Example of a numerical simulation. Flow lines are shown in light blue; contours of the fail function are also shown color coded. At the wellbore surface, black represents catastrophic failure, red represents onset of failure and yellow represents a low risk of failure. Inserts on the right show values of the flow vectors and the fail function along the end crosssections. Similar values are also shown along the plane view of the junction.

3. Failure Criterion

The most common failure criteria in 3D stress analysis are the Drucker Prager, the Lade, and the 2D Coulomb failure criteria (Figure 3). These criteria provide different relationship between rock failure and the three principal stresses ($\sigma_1$, $\sigma_2$, and $\sigma_3$). The 2D Coulomb failure criterion is independent of the intermediate principal stress ($\sigma_2$) and solely depends on the minimum and maximum principal stresses ($\sigma_1$ and $\sigma_3$). The Drucker Prager criterion predicts a substantial increase in rock strength with increasing intermediate principal stress ($\sigma_2$), the Lade criterion predicts a more gradual dependence of strength with the intermediate principal stress. The 3D Coulomb criterion (Ramos et. al., 2002) predicts a linear relationship between the intermediate stress and the rock strength and it can be considered to be a linearized form of the Lade criterion. Using published polyaxial data Ewy (1998) showed that the Lade criterion reproduces the laboratory data well, while the Drucker Prager failure criterion may substantially overestimate the rock strength and the Coulomb criterion may underestimate the rock strength.

The 3D Coulomb criterion reproduces the predictions by the Lade model reasonably well and is considerably simple to implement in numerical modeling. In this work, we used the 3D Coulomb model (with dependence on the intermediate principal stress) for evaluations of multilateral junction failure. Furthermore, the model was calibrated to replicate the failure of horizontal open hole completions (single wellbore) as predicted by Sand 3D.
Figure 3. Failure envelope represented in the $\sigma_2$ vs. $\sigma_1$ stress plane. The Coulomb criterion is independent of the intermediate stress ($\sigma_2$). The Drucker Prager model, Lade model and Modified Coulomb model predict increasing rock strength with increasing intermediate stress.

The failure function based on the 3D Coulomb failure criterion is provided below. These equations were modified to comply with standard mechanical engineering and FEA convention, using positive values to represent tension and negative values to represent compression.

\[
\text{fail} = \left[ (\sigma_1 + p) - Q(\sigma_1 + p) + N \left( 1 + \frac{(\sigma_2 - \sigma_3)}{\sigma_1 - \sigma_3} \right) \right] + C_1 < 0
\]  
\[Q = \left[ \frac{1 + \sin(\phi)}{1 - \sin(\phi)} \right], \]  
\[N = \left[ \frac{2So \cos(\phi)}{1 - \sin(\phi)} \right], \]  

So is the Coulomb cohesion and $\phi$ is the Coulomb friction angle. The critical rock strength to prevent failure is given by:

\[
UCS > \frac{Q(\sigma_1 + p) - (\sigma_3 + p) + C_2}{1 + \frac{\sigma_2 + \sigma_3}{\sigma_1 + \sigma_3}}.
\]

In the above relationships, the coefficients $C_1$ and $C_2$ are obtained by comparing the above calculations with Sand 3D simulations on open hole, horizontal mono-bore stability. Results from 3D FEA simulations are presented as color-coded volumetric plots of failure potential along the multilateral junction. Failure potential is evaluated by plotting the fail function (Equation 1). The condition $\text{fail} = 0$ represents the onset of rock failure. The condition $\text{fail} < 0$ represents catastrophic rock failure. Thus positive values of the fail function represent stability and a diminishing risk of failure; conversely, negative values of the fail function represent increasingly higher degree of failure.

4. In-Situ Stress and Mechanical Properties

Maximum and minimum values of the stress gradients were obtained from multiple Differential Strain Analysis (DSA) laboratory measurements on cores. These values are summarized in Table 1.

Lost circulation analysis from drilling records suggests that $\sigma_h$ gradients as low as 0.624 psi/ft may occur in the field. However, these low minimum stress gradients appear to be associated to fractured sections and in general are...
limited to less consolidated sandstone units (with UCS<1000 psi). Along the more competent sandstones, which are more likely candidates for multilateral placement (i.e., UCS>2000 psi), lost circulation events were not reported and $\sigma_h$ gradients in the range from 0.7 psi/ft to 0.8 psi/ft provide reasonable approximations of the minimum principal stress along the stronger rock sections.

<table>
<thead>
<tr>
<th>DSA Test</th>
<th>$\sigma_h$ (psi/ft)</th>
<th>$\sigma_v$ (psi/ft)</th>
<th>$\sigma_h$ (psi/ft)</th>
<th>$p_p$ (psi/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Value</td>
<td>1.049</td>
<td>0.935</td>
<td>0.801</td>
<td>0.55</td>
</tr>
<tr>
<td>Min. Value</td>
<td>0.983</td>
<td>0.935</td>
<td>0.700</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Rock mechanical properties were measured in the laboratory. These measurements included petrological, physical and mechanical properties. The latter were conducted under conditions of triaxial compression at multiple levels of confining pressure, uniaxial strain compression, unconfined compression, and thick-walled cylinder compression. Some of these values are summarized in Table 2.

<table>
<thead>
<tr>
<th>Measured property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-situ Porosity</td>
<td>33</td>
<td>%</td>
</tr>
<tr>
<td>UCS</td>
<td>2092</td>
<td>psi</td>
</tr>
<tr>
<td>Coulomb Cohesion</td>
<td>850</td>
<td>psi</td>
</tr>
<tr>
<td>Coulomb Friction Angle</td>
<td>31</td>
<td>deg.</td>
</tr>
<tr>
<td>Averaged Young’s Modulus</td>
<td>0.43x10^6</td>
<td>psi</td>
</tr>
<tr>
<td>Averaged Poisson’s Ratio</td>
<td>0.15</td>
<td>N/U</td>
</tr>
<tr>
<td>TWC Strength</td>
<td>4560</td>
<td>psi</td>
</tr>
</tbody>
</table>

5. Extent of Failure at the Tip of the Junction

The extent of the failure at the tip of the junction was evaluated for two cases corresponding to benign and severe conditions of depletion. In both cases, the extent of the highly damaged zone at the tip of the junction, extended approximately 5 to 6 inches in the direction of the wellbores and 1.7 to 2 inches across, defines a volume of failed rock of approximately 10 to 15 in$^3$ (including the symmetrical upper half). This highly localized region of failure occurs under all cases of depletion and drawdown and is a direct consequence of the sharp geometry at the vertex of the junction. In reality, the high stress concentrations in this region will result in rock failure during drilling, and should not be of great concern to long-term stability during production. Analysis of junction stability is thus independent of the failure conditions of the tip of the junction (this localized region of failure was ignored in all cases) and depends on whether the condition for failure (fail<0) is satisfied along the walls of the mother-bore and the lateral wellbore. In all cases, the fail function was evaluated along inner and outer surfaces of the multilateral junction (as shown in Figure 4). Because of the asymmetry of the junction geometry and the resulting bending moments that develop along the mother-bore and the lateral wellbore, the most problematic regions for junction stability are the inner-junction walls.

6. Critical Rock Strength (UCS) to Minimize Risk of Failure

Critical minimum rock strengths (UCS) to minimize the risk of junction failure were calculated using Equation 4. This equation assumes that different strength rocks exhibit the same wellbore strengthening effects (near-wellbore non-linear and non-elastic deformations), and thus similar calibrating coefficients C1 and C2. Given that stronger rocks will have a larger tendency for brittle-elastic failure and smaller near-wellbore plastic behavior, the predicted UCS values may be underestimated. Figures 5 shows an example of the critical minimum rock strength (UCS) required to prevent junction failure for specified field conditions of depletion (800 psi) and drawdown (1600 psi).
Figure 4. Failure predictions were monitored on all surfaces of the junction (Lines 1 through 6). However, because of the asymmetry of the junction geometry and the resulting bending moments that develop along the mother-bore and the lateral wellbore, the most problematic regions for junction stability were the inner-junction walls (Lines 1 and 2).

Figure 5. Example of a calculation to determine the critical minimum rock strength (UCS) to prevent junction failure (Depletion= 800 psi, Drawdown= 1600 psi). Except for a limited region at the tip of the junction (red), the required rock strength for junction stability is 2500 psi (light blue). However, at the inner-junction walls (blue) rock strengths of approximately 3500 psi are required for minimizing the risk of junction failure.

7. Results and Conclusions

The principal results of this study are summarized in Figure 6. The figure shows the failure envelope for the multilateral junction as a function of reservoir pressure (i.e., depletion) and bottom hole flowing pressure (i.e., drawdown). The virgin reservoir pressure line and the depletion line with zero drawdown (45° inclined line) are also shown. In this curve, any condition of depletion and wellbore drawdown is represented by their corresponding values of reservoir pressure and bottom hole flowing pressure. The solid black circles in the figure represent results from sand 3D simulations on a single horizontal well. The continuous line along these points delineates the failure envelope for the horizontal section of the multilateral wellbore, away from the junction. The triangles and color coded lines represent the failure envelope of the multilateral junction. Away from the junction, the monobore can be subjected to considerably higher levels of drawdown and depletion prior to failure. For example, at virgin reservoir pressure the maximum allowable drawdown for the monobore is 1800 psi and for the multilateral junction is 1000 psi (red – medium risk level) to 1200 psi (black level - high risk). At a reservoir pressure of 2000 psi (corresponding to a depletion of approximately 980 psi), the maximum allowable drawdown for the monobore is 1600 psi and that for the multilateral junction is 500 psi (red – medium risk level) to 800 psi (black level - high risk). The minimum rock strength values (UCS) to minimize the risk of failure (white to yellow risk levels) are provided as discrete values below each of the markers. For example, the minimum UCS required for multilateral junction stability at virgin reservoir pressure and a drawdown of 1800 psi is 2800 psi.
Results show that multilateral junctions constructed within weak sandstones (with UCS equal to or lower than 1000 psi) fail even under benign conditions of drilling (i.e., oriented parallel to the maximum horizontal stress and under balanced pressure conditions). During production, the maximum risk of failure occurs at the region of convergence between the two lateral wells and along the wellbore lengths (inner boundaries). Junctions constructed on the medium-strength rock (with UCS approximately equal to 2000 psi) are stable under most drilling scenarios; during production they are stable within a limited range of depletion and drawdown (see Figure 6).

In all cases, the tip of the region of convergence between the lateral wells is at failure; however, this localized region will fail during drilling and thus, should not be of great concern to long-term junction stability.

The size of the region of failure increases for junctions oriented perpendicular to the maximum horizontal stress ($\sigma_H$), and with increasing depletion and drawdown. Under virgin reservoir conditions (no depletion) and limited drawdown (250 to 500 psi), the size of the failure zone along the critical inner boundaries of the junction (Figure 5) is marginal and the risk of junction failure small. However, with increasing depletion and drawdown (red and black lines in Figure 6), the damage along these surfaces is severe and the potential for catastrophic junction failure is high.

Because of the asymmetry of the junction geometry and the resulting bending moments that develop along the mother-bore and the lateral wellbore, the most problematic regions for junction stability are the inner-junction walls; these regions also define the minimum rock strength requirements to assure junction stability. The outer-junction walls are less problematic and less restrictive than the inner-junction walls. The higher effective rock compliance on the side of the junction containing two wellbores results in larger deformations compared to the other side, thus resulting in bending moments along the length of the junction and additional shear stresses at the junction walls. This important effect that is clearly a function of the junction geometry (i.e., difference in diameter between the mother and lateral wellbores and their angle of separation) is ignored by 2D plane-strain approximations. Consequently, predictions using 2D plane-strain approximations will underestimate the conditions of failure. Indeed, most problematic regions for junction stability are located at the inner-junction walls; these regions also define the minimum rock strength requirements to assure junction stability. An additional consequence of this geometrical effect is that (i) short junctions (e.g., 25 ft) are more stable than long junctions (e.g., 50 ft). This is the case under both conditions of drilling and completion operations, and that (ii) smaller lateral diameter wellbores will result in a more stable junction. This effect results from the increased stiffness of the junction to bending.

![Figure 6](image)

Figure 6 Failure envelope for the inner multilateral junction, representing the most restrictive conditions of stability ($\sigma_V = 0.935$, $\sigma_H = 1.049$, $\sigma_h = 0.8$ psi/ft). Envelopes for low risk of failure (Yellow), intermediate risk of failure (Orange) and high risk of failure (Red) are plotted. Minimum rock strength values for minimizing the risk of failure are also provided for various conditions of depletion and drawdown. For example, at 975 psi depletion and 1000 psi drawdown, the minimum UCS value to minimize the risk of failure is 3000 psi. Failure predictions for the mother bore, away from the junction, are shown in black circles.

Given the uncertainty on the in-situ stress, and differing predictions on the minimum horizontal stress, numerical simulations were also conducted to investigate the effect of reducing the minimum horizontal stress on the
stability of the junction. Results indicated that a decrease in the minimum horizontal stress by 0.1 psi/ft reduced considerably the domain of stability. For example, for a 980 psi depletion and 1000 psi drawdown, the minimum UCS to minimize the risk of failure increased to 4000 psi, compared to the required value of 3000 psi for the original case (Figure 5).

![Graph showing reservoir pressure and bottom hole flowing pressure](image)

Figure 6 A considerable reduction in the region of stability results from the decrease of the minimum horizontal stress by 0.1 psi/ft. Minimum rock strength values for minimizing the risk of multilateral junction failure are also provided for three conditions of depletion and drawdown.

In summary, the methodology allows for evaluation of the effect of in-situ stress and junction orientation in relation to the in-situ stress (the latter effect was not discussed in this paper) on junction stability. It also provides means for delineating practical limits for reservoir production (i.e., maximum drawdown at every level of reservoir depletion), and helps to identify the required strength (UCS), within which an open-hole junction will be stable under given field requirements of production (drawdown and depletion).

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8. References


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