WELLBORE STABILITY ANALYSIS FOR PREDICTING SAND PRODUCTION

NGUYEN THE DUC, PHAN NGOC TRUNG, NGUYEN MINH QUY
Vietnam Petroleum Institute

ABSTRACT: Geomechanical stability has become regular consideration from oil exploration to production. Borehole collapse, circulation losses and sand production are costly problems for the petroleum production. In the study presented here, a model based on Mohr-Coulomb failure criterion is used to analyze wellbore stability and predict sand production for a well in a field of Vietnam. The study shows that geomechanical stability analysis can provide valuable supports for selecting wellbore trajectory and controlling sand production. The future works important to wellbore stability analysis for Vietnam fields are also proposed.

INTRODUCTION

In the last two decades, the petroleum industry has witnessed what can be called ‘geomechanics revolution’ and petroleum geomechanics has become the fastest growing commercial area for technical investment within the service sector [1]. Geomechanical stability plays an important role in the development of long and deep wells. The geomechanical instability is usually faced in the drilling with high rig rates in deep water, the drilling in tectonic fields, salt-domes, high-pressure high-temperature fields, and the drilling of more horizontal, highly deviated and multilateral wells ([2]-[4]). Another problem requiring geomechanical stability analysis is related to sand production ([5]-[7]). Production of reservoir fluids at high rates (low bottomhole flowing pressure) cause an increase in the induced tangential stresses concentrated on the face of an open hole or on the walls of perforations in a cased hole. If these induced stresses exceed formation in situ strength, the formation will fail and sand could be produced together with fluids of reservoir. Therefore, sanding prediction needs a knowledge about the mechanisms upon which the rock failure has occurred. It is very important to exactly determine what mechanism has caused the problem of formation instability.

Instability of formation around a borehole (or perforation tunnel) is usually evaluated with a combination of constitutive models and failure criteria ([2], [8], [9]). Constitutive models are a set of equations used to determine the stresses around the hole. In this study, stability analyses have been performed by using a combination of linear elastic constitutive model and Mohr- Coulomb failure criteria. The method has been employed to analyze wellbore stability for three case studies with different stress regimes. The calculated results show the effect of inclination and azimuth on wellbore stability is strongly dependent on in-situ stress state. For the most stable wellbore of each case, the analyses are also carried out for examining the influence of reservoir depletion on the potential of sanding.

DESCRIPTION OF ANALYTICAL MODEL

In this study, stability analyses have been performed by using a combination of linear elastic constitutive model and Mohr- Coulomb failure criteria.

The holes of wellbore (or perforation tunnel) and their adjacent formation are often approximated as thick-walled hollow cylinder. Assume that the principal stresses in the virgin formation are: σ_v, the vertical stress, σ_H the largest horizontal stress, and σ_h, the smallest horizontal stress. A coordinate system (x', y', z') is oriented so that x' is parallel to σ_H, y' is parallel to σ_h, and z' is parallel to σ_v (i.e. z'-axis is vertical). For convenience, the stresses in the vicinity of the deviated hole are in a coordinate system (x, y, z) where the z-axis is parallel to the hole, y- axis to be horizontal, and x-axis to be parallel to the lowermost radial direction of the hole (see Figure 1).

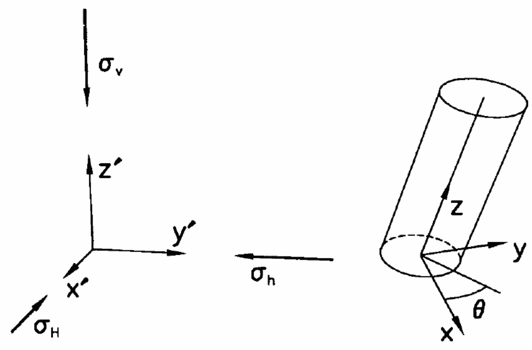

Figure 1 Coordinate system for a hole [2]

The coordinate transformation from system (x', y', z') to system (x, y, z) are obtained by two operations: 1) a rotation $\hat{a}$ round z'-axis, and 2) a rotation $\hat{i}$ around the y-axis (see Figure 2). The angle $\hat{i}$ represents the hole inclination and the angle $\hat{a}$ represents the azimuth angle.

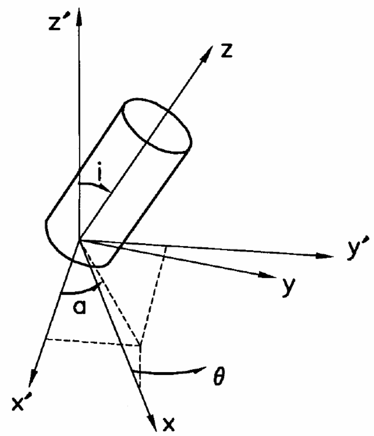

Figure 2 Coordinate transformation [2]

The transformation is described mathematically by the following direction cosines:

$l_{xx'}$, $l_{xy'}$, $l_{xz'}$-The cosines of the angles between x-axis and x', y', z'-axes, respectively.

$l_{yx'}$, $l_{yy'}$, $l_{yz'}$-The cosines of the angles between y-axis and x', y', z'-axes, respectively.

$l_{zx'}$, $l_{zy'}$, $l_{zz'}$ -The cosines of the angles between z-axis and x', y', z'-axes, respectively.

These cosines are related to the inclination angle $\hat{i}$ and the azimuth angle $\hat{a}$ as:

$$
\begin{array}{lll}
l_{xx'} = \cos\hat{i}\cos\hat{a} & l_{yx'} = -\sin\hat{a} & l_{zx'} = \sin\hat{i}\cos\hat{a} \\
l_{xy'} = \cos\hat{i}\sin\hat{a} & l_{yy'} = \cos\hat{a} & l_{zy'} = \sin\hat{i}\sin\hat{a} \\
l_{xz'} = -\sin\hat{i} & l_{yz'} = 0 & l_{zz'} = \cos\hat{i}
\end{array}
\quad (1)
$$

The formation stresses σ_H, σ_h and σ_v are calculated by:

$$
\begin{aligned}
\sigma_x^0 &= l_{xx'}^2\sigma_H + l_{xy'}^2\sigma_h + l_{xz'}^2\sigma_v \\
\sigma_y^0 &= l_{yx'}^2\sigma_H + l_{yy'}^2\sigma_h + l_{yz'}^2\sigma_v \\
\sigma_z^0 &= l_{zx'}^2\sigma_H + l_{zy'}^2\sigma_h + l_{zz'}^2\sigma_v \\
\tau_{xy}^0 &= l_{xx'}l_{yx'}\sigma_H + l_{xy'}l_{yy'}\sigma_h + l_{xz'}l_{yz'}\sigma_v \\
\tau_{yz}^0 &= l_{yx'}l_{zx'}\sigma_H + l_{yy'}l_{zy'}\sigma_h + l_{yz'}l_{zz'}\sigma_v \\
\tau_{zx}^0 &= l_{zx'}l_{xx'}\sigma_H + l_{zy'}l_{xy'}\sigma_h + l_{zz'}l_{xz'}\sigma_v
\end{aligned}
\quad (2)
$$

Here the superscript 0 indicate that these are the virgin formation stresses. Equations (2) represent the stress state in the case of no hole in the formation. The stress state will change when a hole exists in the formation. For the case of cylindrical hole, it is convenient to present the stresses in cylindrical coordinate (r, θ, z). By assuming that there is no displacement along z-axis (plane strain condition), a derivation of the stress solution around cylindrical hole can be found and the stresses at the hole wall are given by the following equations:

$$
\begin{aligned}
\sigma_r &= p_w \\
\sigma_\theta &= \sigma_x^0 + \sigma_y^0 - 2(\sigma_x^0 - \sigma_y^0)\cos(2\theta) - 4\tau_{xy}^0\sin(2\theta) - p_w \\
\sigma_z &= \sigma_z^0 - \nu\left(2(\sigma_x^0 - \sigma_y^0)\cos(2\theta) - 4\tau_{xy}^0\sin(2\theta)\right) \\
\tau_{r\theta} &= 0 \\
\tau_{\theta z} &= -2\tau_{xz}^0\sin\theta + 2\tau_{yz}^0\cos\theta \\
\tau_{rz} &= 0
\end{aligned}
\quad (3)
$$

where p_w is pressure at the wall of hole, ν is Poison's ratio and θ indicate the angular position around the hole (see Figure 2).

As failure is governed by the principal stresses σ_i, σ_j, σ_k, the following matrix equation defines planes of principal stress,

$$
\begin{bmatrix} \sigma_r & 0 & 0 \\ 0 & \sigma_\theta & \tau_{\theta z} \\ 0 & \tau_{\theta z} & \sigma_z \end{bmatrix} = \begin{bmatrix} \sigma_i & 0 & 0 \\ 0 & \sigma_j & 0 \\ 0 & 0 & \sigma_k \end{bmatrix} \quad (4)
$$

Taking the determinant of the above matrices, the principal stresses are given by the following eigenvalue equation:

$$
(\sigma_r - \sigma)\left\{(\sigma_\theta - \sigma)(\sigma_z - \sigma) - \tau_{\theta z}^2\right\} \quad (5)
$$

By solving above equation, the principal stresses acting on the hole wall are given as,

$$\begin{aligned}
\sigma_i &= p_w \\
\sigma_j &= \frac{1}{2}(\sigma_\theta + \sigma_z) + \frac{1}{2}\sqrt{(\sigma_\theta - \sigma_z)^2 + 4\tau_{\theta z}^2} \\
\sigma_k &= \frac{1}{2}(\sigma_\theta + \sigma_z) + \frac{1}{2}\sqrt{(\sigma_\theta - \sigma_z)^2 + 4\tau_{\theta z}^2}
\end{aligned} \tag{6}$$

and the maximum and minimum stresses acting on the hole wall will be as follow,

$$\begin{aligned}
\sigma_1 &= \max\lfloor \sigma_i, \sigma_j, \sigma_k \rfloor \\
\sigma_3 &= \max[\sigma_i, \sigma_j, \sigma_k]
\end{aligned} \tag{7}$$

For evaluating collapse of hole wall, the Mohr-Coulomb failure criterion is employed (for example, see [2], [3], [6]). This is governed by the maximum and the minimum stresses. Fig. 3 shows the Mohr-Coulomb criterion and a Mohr's circle that touch the failure line.

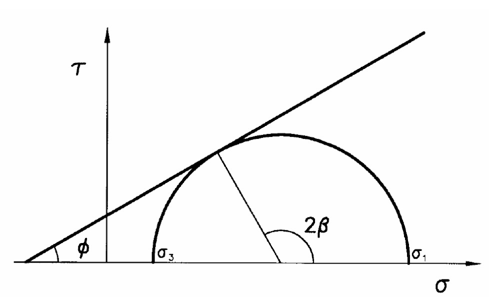

Figure 3 Mohr-Coulomb failure criterion in $\tau - \sigma$ space

The Mohr-Coulomb criterion can be expressed mathematically as follows,

$$\tau = \tau_0 + \sigma \tan\phi \tag{8}$$

where, τ and σ are shear and normal stresses respectively, τ_0 is the inherent cohesion and ϕ is the angle of internal friction.

The shear and normal stresses can be calculated as,

$$\begin{aligned}
\tau &= \frac{1}{2}(\sigma_1' - \sigma_3')\cos\phi \\
\sigma &= \frac{1}{2}(\sigma_1' + \sigma_3') + \frac{1}{2}(\sigma_1' - \sigma_3')\sin\phi
\end{aligned} \tag{9}$$

where, σ_1' and σ_3' are maximum and minimum effective stresses which can be calculated as,

$$\begin{aligned}
\sigma_1' &= \sigma_1 - \alpha p_0 \\
\sigma_3' &= \sigma_3 - \alpha p_0
\end{aligned} \tag{10}$$

where, p_0 is pore pressure and α is Biot's coefficient.

Combining the equations above, the failure condition becomes:

$$(\sigma_1' - \sigma_3') - (\sigma_1' + \sigma_3')\sin\phi = 2\tau_0\cos\phi \tag{11}$$

According to Equation (6), in the case of collapse of wellbore or perforation tunnel at low hole pressures, σ_j will be the maximum principal stress σ_1, and σ_i will be the minimum principal stress σ_3.

The modeling method described above have been used to write a computer program (using FORTRAN programming language) which is able to predicted collapse condition of the hole wall for any combination of in-situ stress state and pore pressure. The calculation requires values of the following input parameters at the depth of the studied formation: (a) the in situ stresses and pore pressure, (b) the cohesion, internal friction angle and Poisson's ratio, and (c) the wellbore inclination and azimuth.

RESULTS AND DISCUSTION OF CASE STUDIES

Measured data from a field of Vietnam are used in our case studies presented here: The sandstone has a cohesion of 1783 psi, a friction angle of 44.2 degree, and a Poison's ratio of 0.15. At a production depth of 11142 ft, the vertical stress is equivalent to the overburden pressure, equal to 10956 psi, the pore pressure is taken at 4836 psi, and the Biot's factor is set to 0.7 as suggested by most authors. The analysis of available FIT/LOT data suggested that the minimum horizontal stress equal to 9036 psi. However, no information can be employed to exactly determine the maximum horizontal stress. In order to cover potential uncertainty range, analyses have been performed for three cases with different maximum horizontal stresses:

1. Base case: $\sigma_H = 1.1\sigma_h = 9940\,psi$
2. Low stress case: $\sigma_H = \sigma_h = 9036\,psi$
3. High stress case: $\sigma_H = 1.2\sigma_h = 13147\,psi$

It is well known that the stress state is usually classified into three different stress regimes based on the relative magnitude between the vertical and horizontal stresses (see [2], [12]). Normal or extensional faulting (NF) stress regimes are associated with $\sigma_v \geq \sigma_H \geq \sigma_h$, reverse or compressional faulting (RF) stress regimes are associated with $\sigma_H \geq \sigma_h \geq \sigma_v$, and strike-slip (SS) stress regimes are associated with $\sigma_H \geq \sigma_v \geq \sigma_h$. According to the classification, the base case and the low stress case are in NF stress regime and the high stress case is in RF stress regime. The difference between the base case and the low stress case is that the first is in isotropic horizontal stress state while the second is in the stress state of horizontal anisotropy.

The program has been used to study influence of inclination and azimuth on wellbore stability. The minimum bottomhole flowing pressures (BHP) for wellbore stability are calculated with different inclinations ($\hat{i}$) and azimuths ($\hat{a}$). The results are shown in Figures 4-6.

From the calculated results of the base case presented in Figure 4, it is apparent that a vertical wellbore is more stable than a horizontal wellbore with all azimuths. However, the optimum drilling trajectory is not necessarily vertical. In this case, the most stable wellbore is a 40^o-deviated one and in a plane parallel to the minimum in situ stress σ_h.

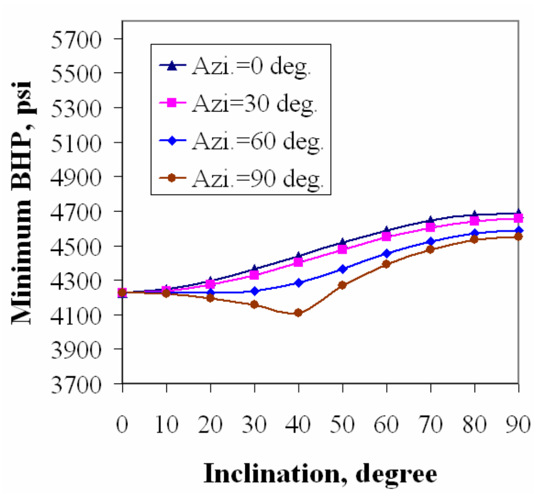

Figure 4 Critical Bottomhole Pressure as functions of inclination (base case)

The calculations of minimum bottomhole pressure for the low stress case are presented in Figure 5 for different wellbore inclination and azimuths. Because of the isotropic horizontal stress state of this case, the results should be independent of wellbore azimuth angle. This expectation is clearly shown in Figure 5 where plots associated with different azimuths are in the same. For this case, the most stable trajectory is exactly vertical, that is inclination angle $\hat{i} = 0^o$.

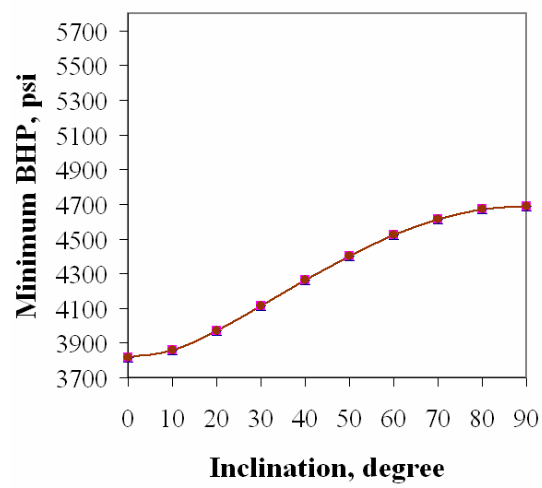

Figure 5 Critical Bottomhole Pressure as functions of inclination (low stress case)

Figure 6 presents calculated results for the high stress case. The case is in an RF stress regime with anisotropic horizontal stress. Contrary to two above cases, the most stable wellbore inclination is horizontal. The most stable wellbore trajectory is associated with a horizontal wellbore which has the azimuth angle equal to 30^o.

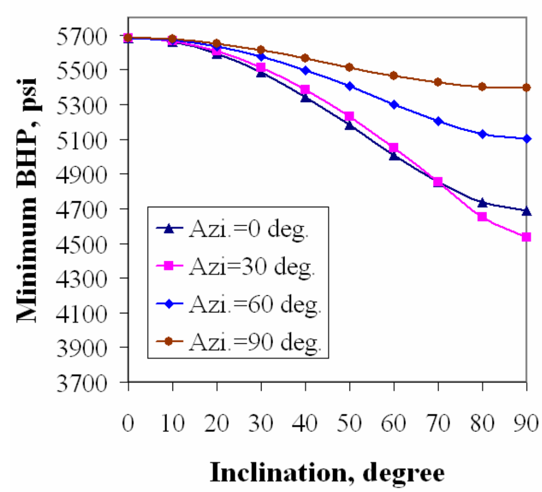

Figure 6 Critical Bottomhole Pressure as functions of inclination (high stress case)

In summary, the study on the effect of wellbore inclination and azimuth indicates that: vertical boreholes will minimize the potential borehole instability only when the stress state is horizontally isotropic and in NF stress regime. Having anisotropic horizontal stress and/or being in RF stress regime will divert the most stable well path from the vertical direction. In these situations, deviated and horizontal wellbores are potentially more stable than vertical wellbores. The inclination and azimuth of the most stable wellbore should be determined exactly by geomechanical stability analyses.

The aforementioned calculations are obtained with the initial reservoir (pore) pressure. However, the reservoir pressure may be decreased during production process. In order to show the influence of reservoir depletion, the analyses have been carried out for these three cases with different reservoir pressures. For each case, the most stable wellbore trajectory (inclination and azimuth) is used in the calculation. The obtained results for base case, low stress case, and high stress case are shown in Figures 7-9, respectively. For these figures, it should be noted that the bottomhole pressure must be lower than reservoir pressure in a production well. Therefore the operating points must be in the lower-right half part of the graph. This part is then divided into sand free operating envelope and sand failure zone.

The sand free operating envelope plot for the base case is seen in Figure 7. As the reservoir pressure decreases from 4836 psi (initial reservoir pressure) to 3800 psi, the minimum bottomhole pressure of sand free production decreases from 4108 psi to 3800 psi (i.e. maximum drawdown pressure decreases from 728 psi to 0 psi). It means that the well can not produce without sand failure when the reservoir pressure decreases below 3800 psi.

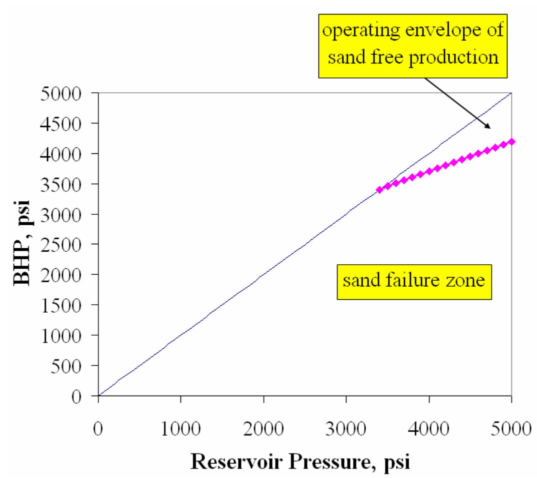

Figure 7 Sand free operating envelope plot (base case)

Figure 8 shows the sand free operating envelope plot for the low stress case. As the reservoir pressure decreases from 4836 psi to 2800 psi, the minimum bottomhole pressure decreases from 3818 psi to 2800 psi (i.e. maximum drawdown pressure decreases from 1018 psi to 0 psi). It means that the well can not produce without sand failure when the reservoir pressure below 2800 psi. The sand free production period in this case is therefore can be longer than in the base case.

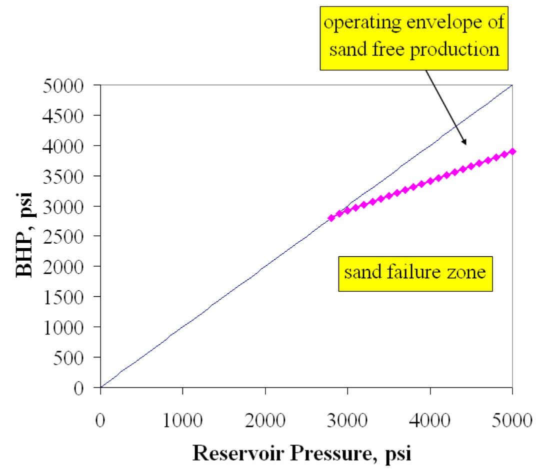

Figure 8 Sand free operating envelope plot (low stress case)

For the high stress case, the sand free operating envelope plot is presented in Figure 9. At the initial reservoir pressure of 4836 psi, the minimum bottomhole pressure is equal to 4534 psi. The well can not produce without sand failure when the reservoir pressure below 4200 psi. It means that the operating envelop of sand free production in this case is much smaller than the ones in two previous cases.

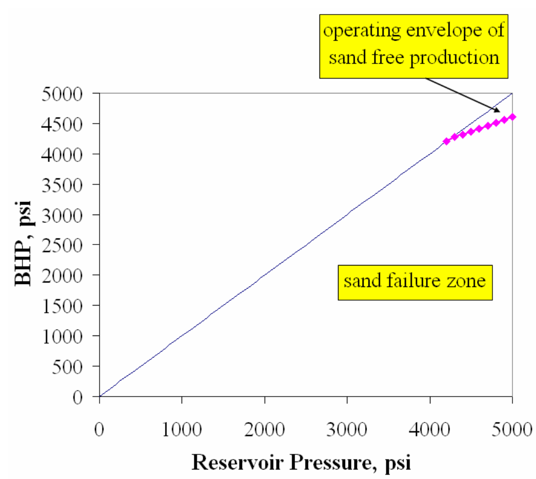

Figure 9 Sand free operating envelope plot (high stress case)

CONCLUSION

- A method for analyzing geomechanical stability of the holes has been presented. Wellbore stability analyses using the presented method have been performed for some case studies. The obtained results show the influences of well inclination, well azimuth, and reservoir depletion under different stress regime.

- The presented study results shows methodology can be employed in: Predicting onset of sanding production for existing free-sanding well; Determining optimum drawdown for existing sanding well; Optimizing wellbore trajectory / perforation direction to minimize instability problem for future infill well.

RELEVANT ISSUES & FUTURE WORK PROPOSALS

- Constitutive models for determination of stresses around the hole range from simple linear elastic models to sophisticated poro-elasto-plastic models. There are also various failure criteria which are used to determine the onset of failure in the rocks. Linear elastic constitutive model and Mohr- Coulomb failure criterion have been used in this work. However, the performance of other constitutive model and rock strength criteria should be evaluated in order to find the most suitable model for typical Vietnam fields.

- The unconfined compressive strength (UCS) and angle of internal friction (Φ) of sedimentary rocks are key parameters needed to analyze wellbore stability. In practice, the problems must usually be addressed when core samples are unavailable or very limited. As a practical approach to these problems, many studies worldwide use ANN or other relations that relate rock strength to geophysical well logs. The study on this approach for Vietnam field should be carried out.

- The weakening effect of water on rock strength has been recognized. Because most oil-gas fields in Vietnam use water injection for pressure maintenance, it is necessary to study for evaluating and modeling the effect of watercut increase on strength of typical reservoir rocks in Vietnam.

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