Solution for Sand Production Problem in Oil and Gas well

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Abstract. Sandstone reservoir rock failure due to hydrocarbon extraction and pore pressure reduction can induce phenomenon called sand production. Even though sand production may increase the overall productivity especially in heavy oil, it also may cause other negative impact such as equipment erosion which can lead to loss of integrity that can eventually induce hydrocarbon leakage. Thus, safety factors need to be considered before deciding if sand production can be allowed in the well. Operators must be prepared for any additional cost for special well completion plan if their well is sanding candidate. Therefore, predicting the sand production ahead of field development plan is smarter exercise for better return of investment. Estimating where and when sand production will occur can be achieved by conducting fit for purpose geomechanical modelling for the specific reservoir. Summary of the methodology is discussed in the paper which can help completion engineer to make decision in selecting best completion. Data from a gas field and well are used in this paper adopting the suggested methodology. The results from the study can predict when and where sand production will occur and the level of severity. The study also recommends simple solution to avoid any sand production by optimising perforation phasing and its geometry.

1. Introduction
Sandstone reservoir rocks contributed to 60% of world hydrocarbon reserves and 50% of the wells completed in sandstone reservoirs have risk of sand production. Thus, the well completion strategy should be based on the severity of sand production for life of the field/reservoir. To design a cost effective well completion design, it is important to evaluate the sand production mechanism for the well. This evaluation should be conducted to answer two main questions, i.e. when and where the sand production will occur honoring the formation depletion. Upon answering these questions, the completion/production engineer is able to then decide if the sand production is still a risk. They may decide either to avoid or control or manage the sand production at the surface. Managing produced sand at the surface might need better tubing and well head design such as chrome material to avoid any erosion caused by the produced sand. The sand production phenomenon is two-stage process. The process starts from the initiation of reservoir rock failure caused by stress exerted on the rock due to
drawdown pressure. This is followed by a second stage where the failed sand grains are transported to the surface by fluid velocity. Sometimes, if the fluid velocity is not sufficient to move the sand grains upwards, it may get deposited at the bottom of the hole Amarmentor et al. [1]

Numerous failure criteria have been developed and are readily available. Even though most of them were developed for civil engineering purposes, petroleum industry adopted some of these criteria for sub-surface reservoir rocks. Unfortunately, most of the criteria are not able to capture the elastoplastic non-linearity of the geomaterial including post-failure in a single constitutive model. As for petroleum industry applications, rock mechanics play vital role for wellbore instability, sand production, hydraulic fracturing, compaction, subsidence etc. Unlike civil engineering applications, where zero tolerance of failure is a must for the design, petroleum industry has to allow some failure of the rock and manage it during operations. Thus, non-linearity and post-failure mechanisms are essential to evaluate the risk and consequences; and we address this in our work.

2. Rock failure mechanism

It is postulated that for sand production to occur, the rock has to fail first. Thus, it is important to understand the types of potential failure mechanisms. There are three types of failure mechanism modes that can normally cause sand production in a reservoir rock namely compression, tension and pore collapse as shown in Figure 1, where $q$ in the y-axis is known as deviatoric-stress and $p'$ in the x-axis ($p'$) is the mean effective stress where $p' = (\sigma_1' + \sigma_2' + \sigma_3')/3$.

![Figure 1](image.png)

**Figure 1.** Illustration of typical mode of rock failure due to stress change in the rock [2, 3]

2.1. Compression/shear failure mode

Reservoir rock underdoings production and depletion can cause stress changes around the borehole or perforation tunnel. The stresses acting on the rock can compress the rock and fail the rock under compression. The rock failure under compression model occurs due to high shear stress acting on the rock exceeding the compressive strength of the rock[4, 5]. Figure 2 show the normal and shear stress acting on a rock sample and stress tensor. The stress tensor is normally used as an input in any failure criteria to evaluate the intensity of compression on the rock and if that can cause any failure[6].
\[ \begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix} \]

(a) Normal and shear stress on planes  
(b) Stress tensor

Figure 2. Illustration of both normal and shear stresses acting on rock sample and stress tensor

2.2. Tension/tensile failure mode
Tensile failure mode of a sandstone reservoir is known as tensile failure. Very high flow rate during production may cause such type of failure mode [7, 8]. However, sand production due to tensile failure occurs infrequently in many oilfields. Even it happens, it will induce lower volume of sand production and normally stabilizes quickly compared to shear failure mechanism [8, 9].

2.3. Pore collapse mode
The pore collapse mode of failure predominantly occurs in very high porosity reservoir rock. Many researchers and practitioners conducted studies related to this type of failure for other issues such as compaction and subsidence [9]. The failure occurs due to overstressed rock which may cause the grains to be unbonded. This will then cause some kind of twisting and rearrangement the grain into the voids (pore spaces). The overall process eventually leads to reservoir rock gets compacted and porosity can reduce significantly. Therefore, the local extreme forces (normally shear) on the grains and grain contacts manifest the failure [7]. Awal et al. [10] conducted a study related to this type of failure mechanism on two wells. They found that the pore collapse failure mechanism is feasible and can induce sand production. Alireza et al. [11] studied the similar phenomenon in laboratory and numerical analysis. They concluded that the combination of drawdown and depletion of the reservoir can lead to pore collapse in the reservoir rock. Meanwhile, Souley et al. [3] also introduced a new constitutive model for sandstone pore collapse, which can be also used for sand production prediction. However, in this paper we will only going to evaluate the sand production related to shear failure as pore collapse need advance modeling technique using numerical model.

3. Geomechanical modelling
The reservoir rocks have definite mechanical behaviors caused by man-made disturbances such as excavation and changing pressures in the porous rock (production/injection). Therefore, understanding of these disturbances to the applied stresses and the associated strains (deformation) is essential for rock failure. We need to quantify the mechanical competency and the in-situ stresses for all geomechanical analyses and sanding risk. Therefore, it is essential to correctly constrain these properties and parameters. This can be achieved by constructing fit for purpose, but robust Mechanical Earth Model (MEM) for reservoir rock [12, 13]. The normal approach for any geomechanics analysis is to integrate all available data such as drilling information, mud logs, open hole logs, sonic logs, seismic, pore pressure measurement etc. In other word, the available data should be able to give indications of the rock strength, elastic properties, in-situ stresses, pore pressure etc. Figure 3 shows a simplified workflow to construct a 1D MEM prior to sand production prediction [14].
4. Sanding production prediction model

Most of the available techniques for sand production analysis are based on either laboratory testing, theoretical modelling or field observations [16]. The modelling techniques can be either analytical or semi-analytical or numerical. Most commonly used sand prediction models are only able to address the problem of "sanding initiation" i.e. the onset of rock failure [17-20]. The reservoir rock is perceived as a medium that deforms poroelastically, infiltrated with fluid which obeys Darcy’s Law [20-25]. The analytical and semi-analytical models, in general, use simple constitutive equations in simple geometries.

In this work, we try to keep the model as simple (analytical) as possible in benefits of quick turnaround time for quick decision yet very robust model. Two different failure criteria were compared, one using conventional Mohr Coulomb and second newly development failure criterion by authors known as ASA (Assef-Surej-Ariffin) model. The fundamental data analysis and preparation is still the same regardless of failure criteria selection that will be used for analytical model. Upon building the MEM the stress around the perforation tunnel need to be computed and then used in the failure criterion. Figure 4 show the far field stress that computed during the MEM construction and how the far field stress will be distributed around a wellbore of perforation tunnel [26]. To compute the stress around the perforation tunnel or wellbore the following equation is used (for vertical well)

\[
\sigma_\theta = \frac{\sigma_H + \sigma_h}{2} \left( 1 + \frac{R_w^2}{r^2} \right) - (P_w) \frac{R_w^2}{r^2} - \frac{\sigma_H - \sigma_h}{2} \left( 1 + 3 \frac{R_w^2}{r^4} \right) \cos 2\theta
\]

\[
\sigma_z = \sigma_v - 2\nu(\sigma_H - \sigma_h) \left( \frac{R_w^2}{r^2} \right) \cos 2\theta
\]

\[
\sigma_r = \frac{\sigma_H + \sigma_h}{2} \left( 1 - \frac{R^2}{r^2} \right) + (P_w) \frac{R_w^2}{r^2} + \frac{\sigma_H - \sigma_h}{2} \left( 1 - 4 \frac{R_w^2}{r^4} + 3 \frac{R^2}{r^4} \right) \cos 2\theta
\]
Figure 4. (a) Schematic of a vertical borehole and far field stresses, (b) the stress distribution for a vertical well and concentration around the wellbore in the direction of horizontal stresses [26]

The above equations define the hoop stress ($\sigma_\theta$), radial stress ($\sigma_r$) and axial stress ($\sigma_z$) as function of the principal stresses, the radial distance $r$ ($r = R_w$ at the wellbore wall) and the direction angle $\theta$. The computed stress around the wellbore, shown in Figure 5, indicates the compression stress calculation one a side of the well. Upon computing all the 6-stress tensor component along the wellbore or perforation tunnel, these stresses will be further rotated along one of the known principal stress direction to infer the maximum ($\Sigma_1$, $\sigma_1$), intermediate ($\Sigma_2$, $\sigma_2$) and minimum ($\Sigma_3$, $\sigma_3$) principal stress to be used in any preferred failure criteria as shown in Figure 5. We used a well data from a gas field for the analysis [8] as shown in Table 1.

Table 1. MEM Data for a reservoir for stress analysis [8]

| Reservoir | Hole Deviation | Hole Azimuth | UCS | Friction Angle | Young Modulus | Poisson's ratio | Overburden Stress | Minimum Horizontal Stress | Maximum Horizontal Stress | Initial Reservoir Pressure |
|-----------|----------------|--------------|-----|----------------|----------------|-----------------|---------------------|--------------------------|---------------------------|---------------------------|
| A         | 50             | 150          | 30  | 40             | 3.5            | 0.2             | 83                  | 68                       | 60                        | 41                        |

Figure 5. Computed stress round a vertical wellbore in pressure unit (MPa) for hoop, radial and axial stresses
### 4.1. Shear Failure Criteria

When we applied a small orthogonal compression stresses (shear stress) on the rock, it might behave elastically. In this case, the rock may deform but it will be able to return to its original position when the stress is released. However, if the shear stress increases exceeding the yield strength of the rock, the sand grains begin to re-orient and form localized shear band. The consequence of this process will be permanent deformation and the rock will not be able to return to its original shape/position. Further increase of the shear stress, the localized shear bands will get connected to each other and form larger shear band where shear failure might occur in a preferential failure angle, $\beta$ as shown in Figure 7. This failure can be modeled using a failure criterion.

**Figure 7.** Shear failure plane on a rock sample in the laboratory due compression

Mohr-Coulomb Failure Criterion: a common criterion of shear failure, is governed by the following equation:

$$\tau = C_o + \mu \sigma_n' \quad \text{or simplified as} \quad \sigma_1' = U_C S + N \sigma_3'$$

where $\tau$ is shear stress, $C_o$ is cohesion of the rock, $\mu$ is coefficient of internal friction, $\sigma_n'$ is effective normal stress. As for simplified version, $\sigma_1'$ and $\sigma_3'$ is effective maximum and minimum principal stresses, $U_C S$ is compressive strength of the rock and $N$ is function of friction angle ($\phi$) of the rock ($N = \frac{1 + \sin \phi}{1 - \sin \phi}$).

We have also developed a new failure criterion for sandstone reservoir rock honoring the rock non-linear plasticity unlike the conventional Mohr Coulomb model adopting linear plasticity. The evolution of the plastic strain tensor $\strain$ accumulates from the point of yielding to post-failure till the rock reaches the residual strength. Our laboratory experimental data illustrate clearly that this evolution is dependent on material strength of reservoir rock and influence of confining pressure. Therefore, the classical constitutive models such as Mohr Coulomb with linear failure surface become contemptible to pronounce the mechanical behavior of materials of such type. Thus, it is very crucial to use a non-linear
failure surface. Encouraged by this, we developed a relation of the failure surface which can be written as below:

\[ F = q' - g(\theta)UCS \left[ A \left( C + \frac{p'}{UCS} \right) \right]^n = 0 \]  

(5)

where: \( p' \) is the effective mean stress; \( q' \) is the deviatoric stress defined by \( q' = \sqrt{\frac{2}{3} S' : S'} \); \( S' \) is the deviatoric stress tensor expressed by \( S' = \sigma' - \frac{1}{3} tr(\sigma')\delta \); \( \theta \) is Lode’s angle; \( UCS \) is the uniaxial compressive strength; \( A \) represents the coefficient of internal friction; \( C \) describes the material cohesion; \( n \) describes the dependency of material failure with effective mean stress; \( \delta \) is Kronecker tensor. Lode’s angle \( \theta \) is defined within the interval \((-\pi/6, \pi/6)\). To consider the influence the third invariant of stress on the shape of the surface, the function \( g(\theta) \) was introduced into the failure surface. Inspired by the previous work of William et al. [27] and applied by Mohamad-Hussein et al. [28].

5. Results for Sanding production prediction

Same dataset from Table 1 has been used for the analysis. Figure 8 shows the geomechanical analysis for sand free drawdown (pore pressure in x-axis and bottom hole flowing pressure, BHFP in y-axis). Drawdown pressure is the difference between Reservoir Pressure and BHFP. The red and blue lines represent the failure lines for ASA and Mohr failure criteria, respectively. Sand production will manifest if the BHFP is below the failure line. The results showed that Mohr failure criterion is more conservative as it does not honor the non-linearity of the reservoir deformation, whereas, ASA model does and suggesting better drawdown and abandonment pressure (critical reservoir pressure for sand free production). Sensitivity has been also conducted on the type of completion and perforation strategy. We found that open hole completion is not in favor for sand free production and cased hole completion with 0-degree oriented perforation is most preferred option, which allows us to produce the well without any sand production throughout life of the field.

![Sand Free Drawdown Analysis](image_url)

**Figure 8.** Sand free drawdown analysis for Well A using Mohr and ASA model
6. Conclusions
In order to provide a best solution for sand production, a geomechanical model i.e. MEM must be constructed and validated using laboratory measurement and all other information such as stress testing, image log, leak-off test etc. A robust MEM is required for better sand production modelling. An appropriate failure criterion is also required to evaluate the onset failure of the rock. The failure criterion must be able to honour the non-linearity of the reservoir rock. In this work, we constructed a MEM for a reservoir rock and conducted sanding analysis to evaluate the rock mechanical behaviour as reservoir pressure changes (depletion). We estimated the maximum drawdown for sand free drawdown using two failure criteria namely Mohr Coulomb and ASA for different types of completion options. It was found that Mohr failure criteria is more conservative compared to newly developed failure criterion (ASA) in estimating sand free drawdown, since ASA model honours non-linear plasticity while Mohr Coulomb doesn’t. However, the sensitivity analysis shows that for sand free production for life of the field it is better to complete the well as cased hole and oriented the perforation on the top and bottom of the borehole (0-degree Phasing). Having said this, it is recommended to conduct production and economic feasibility analysis to check if the proposed option does not hurt any desired production plan/forecast.

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